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## Relationship between airborne electrical and Total Water Content measurements in ice clouds.

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### **Abstract**

During the High Altitude Ice Crystal -High Ice Water Content (HAIC-HIWC) project, instrumented aircraft were flown in the vicinity and inside deep tropical convective clouds. Among the probes installed on one of these aircraft, were the Isokinetic Probe (IKP2), to retrieve the cloud total water content (TWC) and the AMPERA (Atmospheric Measurement of Potential and Electric field on Aircraft) system to provide information on the electrostatic state of the atmosphere and the aircraft.

AMPERA is an electric field mill network which locally measures the electrostatic field at the aircraft fuselage. The distribution and amplitude of the electrostatic field on the aircraft skin depends on the atmospheric electrostatic field around the aircraft and the net electric charge of the aircraft. This latter parameter depends on the balance between the triboelectric current due to the impact of the cloud particles on the aircraft fuselage, the current due to the charged particles emitted by the engines, and the corona current emitted by the aircraft.

Based on the flights of the HAIC-HIWC campaigns, which were conducted almost exclusively in cloud composed of ice particles, a comparison between the total water content recorded by microphysical sensor and the aircraft net charge has highlighted the possibility of deducing an estimate of the TWC from the aircraft electrical potential. In contrast to conventional TWC probes which sample a local area of the atmosphere, the AMPERA system uses the aircraft as a sensor and provides an overall estimation of its net TWC exposure. This study provides the first results of the efficacy of the electrostatic method through comparisons with direct in-situ bulk TWC measurements in ice clouds.

### **1. Introduction**

Since the 1990s, jet aircraft engine power-loss and damage events have been linked to exposures to high ice particle mass concentrations in convective clouds (Lawson et al. 1998, Mason et al. 2006, Flegel, 2018). Such conditions have also been recognized to adversely affect the measurements of air data probes. Engine studies have shown that ice crystals entering the propulsion system’s flow path can alter the thermodynamics and result in internal ice accretion, sometimes resulting in surge, flame-out, or rollback (Mason et al. 2006). Shedding of accreted ice can damage engine internal components. Engine events have usually occurred in conditions that appear benign to pilots, including light-moderate turbulence, low on board weather radar reflectivity, only occasional lightning, and the absence of airframe icing. The typical event is at relatively high altitude and

38 warmer than a standard atmosphere. These types of icing conditions are mostly outside the long-  
39 standing Title 14 Code of Federal Regulations, Part 25 Appendix C conventional cloud icing  
40 certification envelope. In the early 2000s, an Aviation Rulemaking Advisory Committee was  
41 formed to study mixed/phase glaciated icing with the intention of updating icing certification  
42 standards if appropriate. The efforts led to the definition of new standards for icing certification in  
43 Supercooled Large Droplet (SLD) and high ice water content (IWC) conditions, the latter of which  
44 led to the new Title 14 Code of Federal Regulations Part 33 Appendix D (FAA) icing envelope at its  
45 EASA CS-25 Appendix P equivalent (hereafter Appendix D/P). The task of defining the engine  
46 problem, and forming a technical plan for advancing knowledge of the poorly understood ice  
47 crystal icing phenomenon was assigned to the Engine Harmonization Working Group (EHWG), an  
48 association of industry, government and regulatory icing experts.

49 Appendix D/P was developed based on a combination of theoretical calculations and in-situ  
50 measurements taken during the 1950s (Mazzawy and Strapp, 2007). The EHWG agreed that there  
51 were limited cloud measurements to corroborate the Appendix, and recommended new in-situ  
52 measurements of the types of clouds that caused engine events for assessment. In anticipation of  
53 these regulation changes, the European High Altitude Ice Crystals (HAIC; Dezitter, 2013) and North  
54 American High Ice Water Content (HIWC; Strapp et al. 2016) projects formed the international HAIC-  
55 HIWC collaboration to make new in-situ measurements with modern instrumentation and  
56 techniques. The HAIC-HIWC project performed two measurement campaigns, one in Darwin  
57 Australia in 2014, and a second in Cayenne, French Guiana in 2015. Additional independent  
58 measurements were made by HIWC in Florida in 2015, and by HAIC in Darwin and Reunion Island in  
59 2016<sup>1</sup>. The projects aimed to characterize microphysical parameters near convective cores of deep  
60 tropical convective clouds, using common idealized flight plans described by Strapp et al. (2016). The  
61 data have been analyzed and compared to Appendix D/P (Strapp et al. 2019), and will be used in  
62 future ARAC (Aviation Rulemaking Advisory Committee) discussions assessing the suitability of  
63 Appendix D/P.

64 Most HAIC-HIWC measurements (around 92%) were made within mesoscale convective systems of  
65 oceanic origin (Strapp et al. 2019), targeting suspected regions of high Ice Water Content (IWC). In  
66 order to simulate commercial aircraft high IWC exposures, transects across the entire cloud width  
67 were made if possible, passing close to or through convective updraft regions using conventional safe  
68 distances employed by pilots if required. Although there has been no common definition used by the  
69 HAIC-HIWC research team of a high IWC region, Leroy et al. (2017) used a threshold of  $1.5 \text{ gm}^{-3}$  in  
70 their study of ice particle size distributions (PSDs) observed during the HAIC-HIWC flights. Yost et al.  
71 2018 used a nominal threshold of  $1 \text{ gm}^{-3}$  in their study of satellite detection of high IWC regions.  
72 Overall characteristics of the Darwin-2014, Cayenne-2015, and Florida-2015 flight campaign clouds  
73 have been summarized by Strapp et al. (2019). In this study, only the Darwin and Cayenne campaign  
74 data are discussed, because the combination of instruments of primary interest were installed only  
75 for these two projects. The data collection aircraft was the Service des Avions Français Instrumentés  
76 pour la Recherche en Environnement (SAFIRE) Dassault Falcon 20. Although common flight plans  
77 were used, the campaigns differ somewhat in the temperatures at which data were collected. The  
78 Darwin campaign was successful in collecting data at the primary flight levels of  $-30^{\circ}\text{C}$  and  $-40^{\circ}\text{C}$  (10-

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<sup>1</sup> The HAIC project included a focus on, and additional independent flights for the detection of high IWC conditions using new innovative instrumentation concepts.

79 11 km AMSL), but collected limited data at the other primary levels of -10°C and -50°C, partially due  
80 to the early termination of the flight campaign. The Cayenne flight campaign collected data at all 4  
81 primary flight levels, but specifically targeted the -10°C and -50°C levels in order to collect the data  
82 missed in Darwin. Both campaigns targeted oceanic mesoscale-convective systems (MCSs), with the  
83 Cayenne campaign also targeting afternoon continental convection.

84 In both campaigns, the clouds were mostly glaciated, although in Cayenne-2015 a small increase in  
85 mixed-phase cloud was observed due to the greater time spent around the -10 C temperature level.  
86 Overall, mixed-phase cloud comprised less than 5% of the in total in-cloud distance, with narrow  
87 mixed-phase events always less than about 6.2 Nm and with event-average liquid water content  
88 (LWC) less than about 0.32 gm<sup>-3</sup>. The probability of mixed phase cloud decreased with altitude.  
89 Consequently, the comparisons of this article refer almost exclusively to the correlation of the  
90 electric field properties to ice water content (IWC), although small amounts of liquid may also be  
91 present for short periods, which would also be included in the TWC measurement. Further details on  
92 features of the clouds and analyses of the datasets can be found in other HAIC-HIWC articles and  
93 reports (e.g. Leroy et al., 2017; Strapp et al. 2019).

94 One of the goals of the HAIC project was the improvement of methods to detect icing conditions to  
95 reduce the risk of aircraft incidents in such weather conditions (Dezitter, 2013). Different techniques  
96 have been used to retrieve the LWC and/or IWC and/or TWC based on direct measurement, among  
97 them hot wire, flow-through evaporator methodologies, the latter using differential hygrometry  
98 (Brenquier et al., 2013; Baumgardner, 2011) and the ice accretion methodology. A number of sensors  
99 based of one more of these principles were installed on the SAFIRE Falcon-20 for the HAIC-HIWC  
100 campaigns, including the Isokinetic Probe (Davison et al., 2008), the Science Engineering Associates  
101 Robust probe (Strapp et al., 2008; Grandin et al., 2014), the Rosemount Icing Rate Sensor  
102 (Baumgardner, 2011). Other techniques estimate water content through indirect measurements of  
103 the cloud Particle Size Distribution or radar reflectivity. Particle imaging probes, capable of providing  
104 an estimate of the IWC through size to mass conversion (Stratton Park Engineering Co. (SPEC) 2D-  
105 Stereo probe (2D-S), Droplet Measurement Technologies (DMT) Precipitation Imaging Probe (PIP),  
106 Leroy (2016) and the multi-beam Radar SysTem Airborne (RASTA) 95GhZ Doppler cloud radar  
107 providing reflectivity, doppler velocity and an estimation of the IWC as a derived product (Protat et  
108 al., 2009; Delanoe et al. , 2013), were also installed on the Falcon 20.

109 In the framework of the HAIC project, ONERA proposed a new concept for the estimation of the  
110 TWC, based on the measurement of the electrostatic field on the aircraft fuselage. During the HAIC-  
111 HIWC campaigns, a network of electrostatic field meters, called AMPERA (Atmospheric Measurement  
112 of Potential and Electric Field on Aircraft), was installed on the SAFIRE Falcon 20 aircraft. This system  
113 supplies information on the electrostatic state of the atmosphere (Laroche, 2012). The ONERA  
114 approach is based on the concept that the aircraft itself can be used as a sensor to provide  
115 information on cloud TWC through its correlation to electrostatic charging of the aircraft and the  
116 surrounding cloud particles. A charge measurement single sensor developed by the National  
117 Research Council (NRC) of Canada has also been tested within HAIC, although not on the Falcon-20.  
118 Details can be found in Davison et al. (2018).

119 For each flight of the HAIC-HIWC campaigns, a wide variety of sensors has been installed on the  
120 aircraft to sample the microphysical, dynamical and electrostatic characteristics of the atmosphere.

121 In the framework of our study, our interest was focused on microphysical sensors implemented on  
122 the same aircraft as the AMPERA system (the Falcon 20 aircraft). Unfortunately, not all data recorded  
123 by the different sensors were available. Consequently, in this study, comparisons were restricted  
124 between the TWC estimated with the Isokinetic Probe (IKP2) bulk TWC evaporator (Davison et al.  
125 2008, Davidson et al. 2016, Strapp et al. 2016) and the measurements of the AMPERA system.

## 126 **2. Airborne estimation of total water content**

### 127 2.1 Airborne probes for the retrieval of the total water content on research aircraft

128 Sensors which are currently used worldwide on research aircraft for the estimation of liquid and ice  
129 water content during flight have been reviewed exhaustively elsewhere. Different perspectives can  
130 be found in Baumgardner et al. (2011), Brenguier et al. (2013), and Korolev et al. (2017), and only a  
131 brief summary relevant to this study will be given here. The measurement of IWC will be emphasized,  
132 due to the rarity of mixed-phase measurements in the HAIC-HIWC dataset (section 1).

133 A first instrument category estimates ice (or liquid) water content based on the integration of the  
134 particle size distribution and a size to mass conversion. This method requires knowledge of the  
135 effective density variation as a function of the particle size. Uncertainties associated with this  
136 method for IWC come from the wide variety of crystal shapes and densities in nature, and  
137 fundamental uncertainties in the PSD accuracy, such as depth of field uncertainty and out-of-focus  
138 particle sizing corrections (Korolev et al., 1998a; Baumgardner et al., 2011; Abel, 2014; Leroy et al.,  
139 2016). Furthermore, accurate separation of liquid and ice particles in mixed-phase situations is a  
140 largely un-resolved problem for size less than approximately 100  $\mu\text{m}$ .

141 A second category includes the estimation of IWC from combined retrievals of radar reflectivity, the  
142 terminal fall speed of hydrometeors and the Particle Size Distribution (Protat, 2016).

143 A third and more direct technique relies on the measurement of the power used for melting and  
144 evaporating ice particles impacting the surface of a heated hot wire sensor. The Nevzorov probe  
145 (Korolev et al., 1998b) and the SEA Robust probe (Strapp et al., 2008; Grandin et al., 2014) are based  
146 on this principle. One of the main difficulties of these probes for IWC measurement is the relatively  
147 low efficiency for capture and evaporation of ice particles, of the order of 30-50% by some estimates  
148 (Strapp et al., 2008; Grandin et al., 2014; Korolev et al., 2013; Leroy et al., 2017), and the lack of  
149 comprehensive characterization of this efficiency. Furthermore, the LWC efficiency is typically close  
150 to unity, so the deconvolution in mixed-phase conditions requires two sensing wires with differing  
151 LWC and IWC efficiencies (Korolev et al., 1998b; Brenguier et al., 2013), and the accuracy of this  
152 method has not been evaluated in a wide variety of conditions. A single TWC wire can provide very  
153 misleading results in mixed phase conditions due to this LWC vs. TWC efficiency difference.

154 A fourth category relies on the evaporation of hydrometeors and differential hygrometry.  
155 Hydrometeors enter an inlet exposed directly to the air stream. TWC is deduced from the vapour  
156 concentration of evaporated hydrometeors, measured by one or more hygrometers. Among the  
157 probes based on this technique are the Counterflow Virtual Impactor (CVI: Noone et al., 1993; Twohy  
158 et al. 1997), the UK Met Office Total Water probe (Nicholls et al. 1990, Baumgardner et al., 2011;  
159 Abel 2014), the Fast In Situ Stratospheric Hygrometer (FISH: Schiller, 2008; Zöger, 1999), and the  
160 Isokinetic Probe (IKP2; Davison et al. 2008). One potentially large advantage of this technique is that

161 it is possible to obtain near unit efficiency for hydrometeor sampling if the flow is controlled to  
 162 isokinetic values; however, liquid and solid phase cannot not be differentiated with this technique.

163 A further technique employed during HAIC-HIWC for the estimation of LWC used the Rosemount  
 164 icing rate sensor, which is mainly responsive to only the supercooled water droplets (Baumgardner  
 165 and Rodi, 1989; Cober et al., 2001; Baumgardner, 2011). The measurement is based on changes in  
 166 the natural frequency of an oscillating cylinder due to accretion of ice on its surface. Although this  
 167 technique is open to uncertainties, it can be useful in mixed-phase situations when separating the  
 168 LWC and IWC components of the PSD is often difficult using other probes.

169 Table 1 contains a simple and non-exhaustive list of the possible methods for estimating airborne  
 170 TWC during flights with the SAFIRE Falcon-20. As mentioned before, among listed probes, not all data  
 171 are available for our investigations, as the Nevzorov, the CVI and the RICE probe.

172 **Table 1 : Summary of methods and sensors used to estimate airborne total water content on the SAFIRE Falcon-20**

Method	Sensor basing on the method	Measurement campaign	Reference article
Estimation of the TWC based on the integration of the particle size distribution and the mass size conversion	2D-S, PIP	Megha-Tropiques, HAIC-HIWC, HYMEX	Leroy, 2016; Baumgardner et al., 2017; Fontaine, 2014
Measurement of the power used for melting and evaporation of particles impacting a heated hot wire sensor	SEA Robust	HAIC-HIWC	Strapp, 2008 ; Leroy, 2017
	Nevzorov	HYMEX	Korolev, 2013
Differential hygrometry	CVI	POLARCAT	Noone, 1993; Twohy, 1997
	IKP2	HAIC-HIWC	Davidson, 2008; Strapp, 2016
Estimation of the total water content from combined retrievals	RASTA	HYMEX, MEGHA TROPIQUES	Protat 2009, 2016
Change in the natural frequency of an oscillating cylinder (LWC)	RICE	HAIC-HIWC	Baumgardner et al., 2011

173

174 2.2 The HAIC-HIWC TWC reference probe

175 Table 1 lists the probes that were installed on the SAFIRE Falcon-20 during the HAIC-HIWC campaigns  
176 that provided estimates of TWC. During the HAIC-HIWC campaigns, the Isokinetic Evaporator Probe  
177 (IKP2) has been chosen as the reference TWC probe. That's why this probe has been chosen to  
178 investigate the results supplied by the AMPERA system. The Isokinetic Evaporator Probe was  
179 developed by the NRC and Environment Canada specifically for the measurement of the high-  
180 altitude, high speed, high IWC environment (up to 20 hPa, 200 ms<sup>-1</sup>, -50°C, and 10 gm<sup>-3</sup>) with a target  
181 TWC accuracy of 20%, after the EHWG concluded that instruments existing at the time were either  
182 too unreliable or contained uncertainties that could not be sufficiently accurately determined. The  
183 development of the original IKP probe has been extensively documented in the literature (Davison et  
184 al. 2008, 2009, 2010a, 2010b, 2011). The downsizing effort to the IKP2 probe, required for  
185 installation on the Falcon-20, and its extensive wind tunnel testing has been described by Strapp et  
186 al. (2016). System accuracy estimates and equations governing the TWC calculation have been  
187 provided by Davison et al. (2016). The principle of operation of the IKP and IKP2 probes has been  
188 described in the references above, and is repeated briefly here. Cloud particles are ingested in an  
189 inlet facing the incoming air stream. The flow through the inlet system is throttled with a butterfly  
190 valve to approximate the isokinetic value, so that hydrometeors entering the probe have a  
191 concentration and distribution, as close as possible to the concentration and distribution present in  
192 the free atmosphere. The hydrometeors melt and evaporate inside the probe in a spiral evaporator  
193 section. The basic measurement of the probe is then made by sampling the vapour concentration in  
194 the flow path after hydrometeor evaporation. Since that measurement includes contributions from  
195 both the hydrometeors and the pre-evaporation background water vapour (BWV), a separate  
196 measurement of BWV must be made and subtracted from the IKP2 flow path vapour concentration.  
197 For HAIC-HIWC, this background measurement was made off the fuselage of the aircraft with an  
198 independent rear-facing inlet, intended to sample the humidity of the air without ingesting  
199 hydrometeors. Licor-840a hygrometers were used for both the IKP2 and background measurements.

200 System uncertainty estimates for the IKP2 have been provided by Davison et al. (2016) for three  
201 temperature intervals of focus in the HAIC-HIWC flight campaigns. At higher TWCs, uncertainties are  
202 of the order of 2-3%. But the subtraction of BWV becomes increasingly important with increasing  
203 temperature and decreasing TWC, as saturation BWV levels increase exponentially, and typically  
204 exceed 2 g.m<sup>-3</sup> at -10°C. Relatively small fractional errors in the BWV levels thus become important,  
205 particularly at low TWC values. Consequently, system uncertainty calculations increase to of the  
206 order of 50% at -10°C and 0.1 g.m<sup>-3</sup>, and can be further exacerbated by poor synchronization or  
207 differing time response of the IKP2 and BWV measurements. For this reason, the use of the IKP2 is  
208 practically limited to temperatures colder than about 0°C in turbulent tropical atmospheres (Strapp  
209 et al. 2016).

210 During the HAIC-HIWC campaigns, difficulties were experienced measuring BWV due to wetting of  
211 the air sampling lines, and ingestion of ice particles that erroneously enhanced the measurement in  
212 high TWC conditions. Due to the observation that HAIC-HIWC clouds were mostly glaciated, the  
213 decision was made to assume ice saturation concentrations in cloud for all IKP2 TWC calculations.  
214 Some errors could be expected from this assumption. The decision received some support from an  
215 Environment and Climate Change Canada (ECCC) analysis of in-cloud ice supersaturation  
216 measurements on the National Research Council Convair-580 during the only 4 flights with reliable  
217 BWV measurements during HAIC-HIWC, which showed that the average BWV concentrations were  
218 only slightly supersaturated with respect to ice. By randomly injecting BWV errors implied from the

219 above measurements into the HAIC-HIWC dataset, Strapp et al. (2019) first showed that the ice  
220 saturation assumption had little effect on the 99<sup>th</sup> percentile TWC values of most interest to the  
221 EHWG. Furthermore, there was almost no effect overall in the -40°C and -50°C temperature intervals  
222 due to the very low BWV concentrations. The effects were largest in the warmest -10°C temperature  
223 interval, where an overall low-bias was observed for TWCs < 0.6 g.m<sup>-3</sup> (e.g. 20% at 0.1 gm<sup>-3</sup>), and a  
224 high bias for TWCs > 0.6 g.m<sup>-3</sup>, maximizing at about 6% at 1.2 g.m<sup>-3</sup>. In addition to these average  
225 biases however, noise with a standard deviation of approximately ±0.13, ±0.07, ±0.03, and ±0.004  
226 g.m<sup>-3</sup> was added to the IKP2 TWC estimate for the -10, -30, -40, and -50°C intervals respectively,  
227 roughly independent of TWC. Consequently, the ice saturation BWV assumption is expected to  
228 introduce small biases and some scatter, as described above, into the IKP2 TWC and AMPERA  
229 comparisons, particularly for the -10 and -30 C intervals. Scatter is also expected due to the vast  
230 differences in the sample volumes being sampled between the IKP2 and AMPERA, which are typically  
231 about 10<sup>-4</sup> m<sup>3</sup>s<sup>-1</sup> for the IKP2 versus probably greater than 2.10<sup>3</sup> m<sup>3</sup>s<sup>-1</sup> for exposed particle impact  
232 regions on the Falcon-20 which would contribute to the AMPERA measurements.

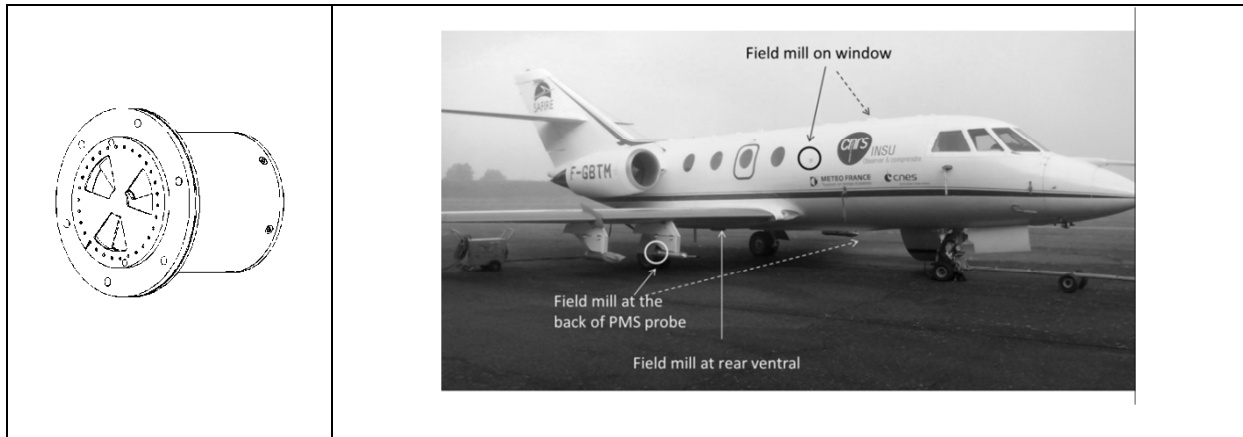
### 233 **3. The AMPERA system**

#### 234 3.1 Field Mill

235 Since the 1940s, there have been many studies estimating the atmospheric electrostatic field in fair  
236 weather conditions, but also in the vicinity and inside thunderstorms. In this framework, different  
237 kinds of airborne sensors have been developed. Design of these sensors depends on the airborne  
238 platforms that carry the instruments (Mac Gorman and Rust, 1998). These include, for example, the  
239 electric field meter (Gun, 1948; Winn, 1993), the rocket borne field meter (Winn and Moore 1971),  
240 the airborne rotating vane field mill (Jones, 1990), the cylindrical field mill (Kasemir, 1972; Mac  
241 Gorman and Rust, 1998) and the rotating field mill on balloons (Chauzy, 1991; Marshall and Rust  
242 1991; Stolzenburg, 1998). In contrast to the rocket or the balloon, the use of aircraft allows a more  
243 comprehensive temporal and spatial analysis of the electrostatic field. Aircraft platforms have  
244 provided the only way to measure the horizontal cross-section of a cloud to date (Christian, 1976;  
245 Merceret et al., 2008). From this perspective, airborne field mills have been adopted for atmospheric  
246 research by ONERA for decades (Laroche, 1986) and tested on different kinds of aircraft (e.g. C160  
247 Transall, Delannoy, 2012; Gloster Meteor NF11, Boulay, 1982; Falcon 20).

248 An illustration of the field mill used during HAIC-HIWC is shown on the left panel of figure 1. The field  
249 mill designed by ONERA differs from other field mills, such as those of Bateman (2007) in that there is  
250 an external grid in front of the measurement electrode. As illustrated on figure 1, there are only  
251 three sectors in the grid of the ONERA field mills through which the external electrostatic field  
252 reaches the measurement electrode.





253 **Figure 1 : AMPERA system.** On the left panel: a picture of the field mill. On the right panel: Illustration of the  
 254 implementation of the AMPERA system on the Falcon 20 aircraft during the HAIC-HIWC campaigns. The locations of the  
 255 field mills comprising the AMPERA system are indicated by arrows.

256 Each rotating-vane field mill measures the electrostatic field at its location on the aircraft. The  
 257 rotating-vane alternately shields and exposes the sensing plate to the external electric field. The  
 258 variation of the charge induced on the measurement electrode is tied to the electric field (Bateman,  
 259 2007). Each field mill on the aircraft skin continuously records the electrostatic field during flight,  
 260 which depends on the atmospheric electric field around the aircraft and the net electric charge of the  
 261 aircraft. The aircraft electrical potential  $V_a$  is equal to the net charge divided by the aircraft  
 262 capacitance  $C_a$ .

263 The characteristics and performance of one field mill, determined from laboratory tests, are detailed  
 264 on table 2. Field mills need to detect both weak electrostatic field as in fair weather (typically, the  
 265 magnitudes are less than 100 and 20  $V.m^{-1}$  near the ground and near 5 km respectively) and strong  
 266 electrostatic fields (typically more than 100  $kV.m^{-1}$ ) inside thunderstorms (MacGorman, 1998). Fair  
 267 weather measurements are used during the calibration phase. For these reasons, the field mills have  
 268 a large dynamic range, as indicated in table 2. Furthermore, field mills have been designed to the  
 269 environment of the aircraft. Most of the time, during the HAIC-HIWC campaigns, the flight envelope  
 270 was from ground level (ca. 1000 hPa and 26°C) to about 12 km (ca. 200 hPa, -50°C). These thresholds  
 271 are consistent with the AMPERA operating environment limits.

272 **Table 2 : Performance and characteristics of each field mill of the AMPERA system**

<b>Physical</b>	Mass	0.870 kg
	Power	28V (DC) ; 25 W max
	Size	120 mm x 115 mm
<b>Dynamic range</b>		+/- 5 V/m to +/- 1 MV/m
<b>Threshold of detection</b>	Below 5 kV/m	5 V/m
	Above 5kV/m	20 V/m
<b>Sampling rate</b>		10 Hz

<b>Operating environment</b>	Temperature	-55 °C to 60 °C
	Pressure min	44.4 hPa (70 000 ft)
	Relative Humidity	5 % to 100 %
	Shock protection	Acceleration peak value 6G
<b>Operating mode</b>	Alimentation and Ethernet connection	

273

### 274 3.2 AMPERA during HAIC-HIWC

275 In order to obtain an estimate of the three components of the atmospheric electrostatic field and the  
 276 aircraft potential, the use of multiple field mills on the same aircraft is required. AMPERA is a field  
 277 mill network (Laroche, 2012) installed on the fuselage of the aircraft, requiring a minimum of four  
 278 field mills. Each field mill is flush mounted in order to reduce electrostatic distortion by the aircraft  
 279 and the sensors. The locations of the field mills have been chosen for symmetry, the sensitivity of the  
 280 potential dependency, and redundancy of measurement.

281 Each field mill brings local information of the electrostatic state on the aircraft surface. All data from  
 282 each field mill of the AMPERA system are synchronized.

283 During the Darwin-2014 and the Cayenne-2015 campaigns, the AMPERA system consisted of a  
 284 network of five field mills. These sensors were installed on window blanks at the rear central fuselage  
 285 and the back of under-wing Particle Measuring System (PMS) probes of the SAFIRE Falcon 20 aircraft.  
 286 The locations of field mills on the Falcon 20 aircraft, used during both campaigns, are identified on  
 287 the right panel of figure 1 and in table 3.

288 [Table 3 : Location of the five field mills of the AMPERA system for the HAIC-HIWC campaign.](#)

<b>Field Mill number</b>	<b>Field mill location of the aircraft</b>
1	At the rear central fuselage
2	On a right window blank
3	On a left window blank
4	At the back of the PMS probes – under the starboard wing
5	At the back of the PMS probes – under the port wing

289

### 290 3.3 Calibration

291 Each field mill of the AMPERA system continuously measures the local electrostatic field on the  
 292 aircraft surface during aircraft flight. The estimation of the atmospheric field components and the

293 aircraft potential are deduced from the signal recorded by the field mill by applying the calibration  
 294 method of Winn (1993). Almost all other methodologies used by the research community (Koshak,  
 295 1994, 2006) rely on the same principle as that used for AMPERA.

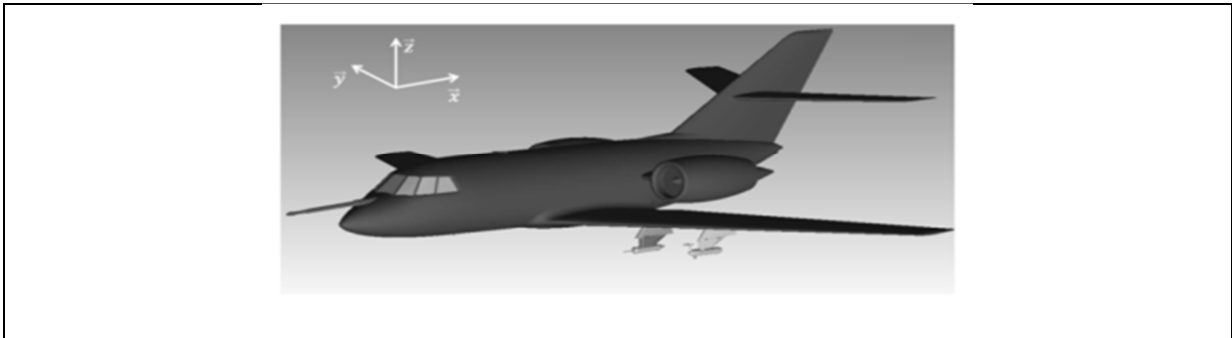
296 Based on the assumption of a uniform atmospheric electrostatic field around the aircraft (Laroche  
 297 1986), a linear relationship can be established between the electrostatic field on the aircraft skin and  
 298 the three components of the atmospheric electrostatic field and the aircraft potential (Bateman,  
 299 2007; Jones, 1990; Laroche, 1986, 2012; Koshak 2006; Mach, 2007, 2015). This relationship can be  
 300 expressed by:

301 
$$E_i = \alpha_i E_{ox} + \beta_i E_{oy} + \gamma_i E_{oz} + \lambda_i V_a \quad (1)$$

302 where  $E_i$  is the electrostatic field recording by an individual field mill;  $E_{ox}$ ,  $E_{oy}$ ,  $E_{oz}$  are the three  
 303 components of the atmospheric electrostatic field;  $V_a$  is the aircraft potential;  $\alpha_i$ ,  $\beta_i$ ,  $\lambda_i$ ,  $\gamma_i$  are  
 304 constants. Each constant is a function of the form factor of the aircraft and can be inferred by in-  
 305 flight calibration and by numerical computations.

306 Nowadays, there are two field mill calibration methodologies commonly used by the research  
 307 community. The first is based on flight calibrations in fair weather, with roll and pitch maneuvers  
 308 (Koshak, 2006; Mach, 2007; Winn, 1993). The second is based on a numerical calculation using a 3D  
 309 mesh shape model of the aircraft (Mazur, 1987).

310 For the HAIC-HIWC project, a Poisson equation solver has been used to numerically compute the  
 311 value of  $E_i$  based on the three-dimensional shape model (Figure 2) of the Falcon 20 aircraft for four  
 312 following configurations detailed in table 4.



313 **Figure 2 : Three dimensional shape model of the Falcon 20 aircraft.**

314 **Table 4: The four configurations used to compute the value of  $E_i$  on the three dimensional model of the Falcon 20**  
 315 **aircraft.**

Configuration	$E_{ox}$ (V/m)	$E_{oy}$ (V/m)	$E_{oz}$ (V/m)	$V_a$ (V)
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1

316

317 Results of the four configurations provide estimates of the  $\alpha_i$ ,  $\beta_i$ ,  $\lambda_i$ ,  $\gamma_i$  coefficients for each field mill  
 318 location. The values of the  $\alpha_i$ ,  $\beta_i$ ,  $\lambda_i$ ,  $\gamma_i$  coefficients for each field mill are combined to form the transfer  
 319 matrix  $\mathbf{M}_{ja}$ . The  $\mathbf{M}_{ja}$  matrix obtained for the HAIC-HIWC campaigns is contained in table 5.

320 **Table 5 : The  $\mathbf{M}_{ja}$  Matrix used**

	$E_x$	$E_y$	$E_z$	$V$
<b>MAC 1</b>	0.1	0	-1.65	0.15
<b>MAC 2</b>	2	-1.4	0.6	0.2
<b>MAC 3</b>	2	1.4	0.6	0.2
<b>MAC 4</b>	1.1	-2.7	-4.4	0.6
<b>MAC 5</b>	0.55	5	-4.5	0.65

321

322 The linear equation (1) is applied to the HAIC-HIWC field mill configuration (five field mills as  
 323 described previously – see figure 1). The five linear equation system can be expressed as the  
 324 following:

325 
$$E_m = \mathbf{M}_{ja}A \quad (2)$$

326 where  $E_m$  is an array of measurements recorded by field mills,  $\mathbf{M}_{ja}$  is a transfer matrix, which contains  
 327 all constant coefficients, and  $A$  is the desired array of the three components of the local electrostatic  
 328 ( $E_{ox}$ ,  $E_{oy}$ ,  $E_{oz}$ ) field and the aircraft potential ( $V_a$ ). The  $A$  matrix is found by inverting equation (2),  
 329 which is least square determination of the matrix  $A$  (Laroche, 1986). The  $A$  matrix resolved is  
 330 expressed as the following:

331 
$$A = (M_{ja}^T \cdot M_{ja})^{-1} M_{ja}^T E_m \quad (3)$$

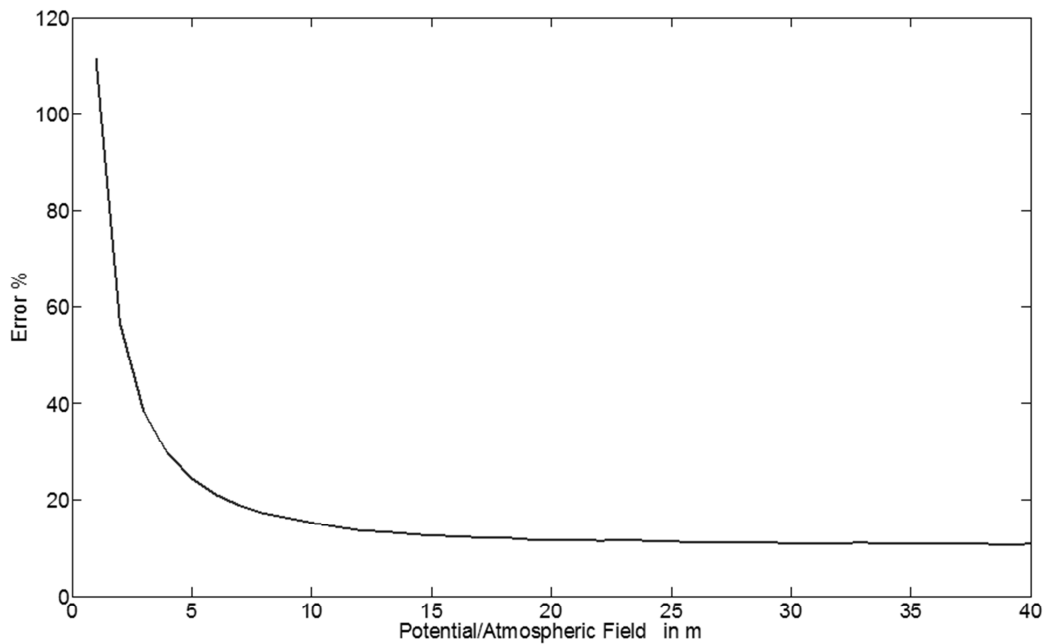
332 Mazur (1987) and Mach (2009) have shown that there are different sources of error associated with  
 333 this methodology.

334 The accuracy is dependent on two causes: the  $\mathbf{M}_{ja}$  coefficient matrix which reflects the airplane form  
 335 factor, i.e. the link between ambient and local field and the measurement of electrostatic on aircraft  
 336 surface.

337 The total error on the evaluation of the aircraft potential  $V_a$  are computed by considering a random  
 338 error on each measurement ( $E_m$ ) and on each computed element of the matrix  $\mathbf{M}_{ja}$ . Despite a careful  
 339 sensors calibration in laboratory and on the aircraft, we consider an overall relative error in the  
 340 measurement of 2 %. For the matrix coefficient,  $\mathbf{M}_{ja}$ , the considered error was +/- 5%.

341 The errors on  $V_a$  depends on the electrical state of the atmosphere ( $E_x$ ,  $E_y$ , and  $E_z$ ) and the relative  
 342 magnitude of the aircraft potential. The relative error computation has been calculated with an  
 343 atmospheric field of 1 V/m in the aircraft referential. Each components of the atmospheric  
 344 electrostatic field are fixed to 1 V/m. For this state of the atmosphere, the error on the aircraft  
 345 potential has been estimated for different value of aircraft potential. Results are presented on figure

346 3. The figure 3 shows the evolution of the error on  $V_a$  versus  $V_a$  magnitude weighted by the norm of  
347 the atmospheric electrostatic field.



348

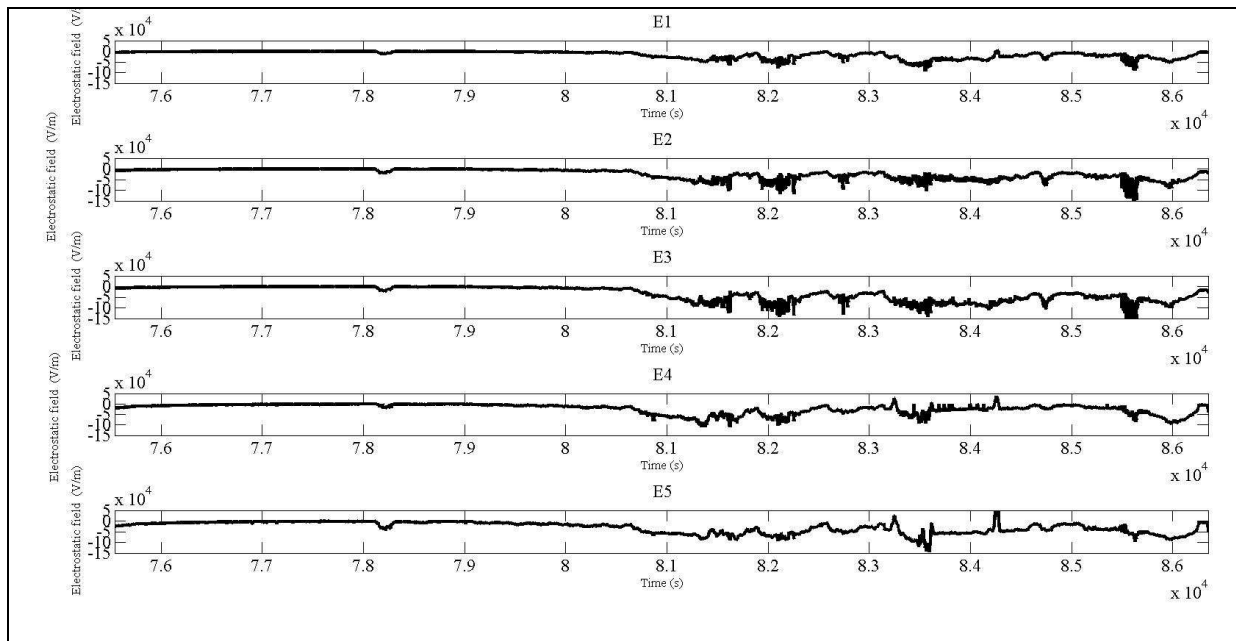
349 *Figure 3 : Relative error on the computation of  $V_a$  versus the ratio  $V_a/E_a$  for +/- 2 % error on measurement of electric field*  
350 *on the aircraft and +/-5 % error on computation of matrix  $M_{ja}$  elements.*

351 When magnitude of the atmospheric field is between 10 and 20 times lower than the magnitude of  
352 the aircraft potential, the relative error on the evaluation of the potential range between +/- 15 %  
353 and +/- 10 %.

354 For the SAFIRE Falcon-20 in HAIC-HIWC, due to this error, the minimum detectable atmospheric  
355 electrostatic field is about  $1000 \text{ V.m}^{-1}$  when the aircraft potential has a magnitude of 100 kV.

#### 356 3.4 Recording by the AMPERA system

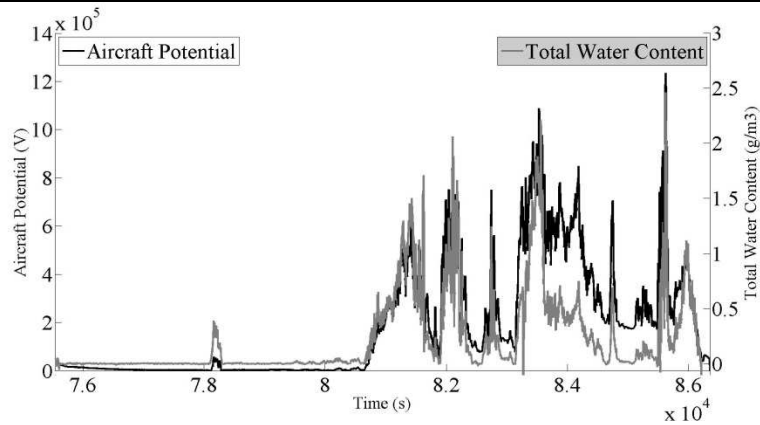
357 An example of the methodology and results obtained with the AMPERA system is given on figure 4,  
358 for flight FS14019 (02/09/2014) of the Darwin-2014 campaign. The measurements are in ice clouds  
359 with no LWC present, initially at a temperature of -37 C, and in the later part of the sequence at -47  
360 C. The take-off and landing times of this flight were 20:48 and 00:14 UTC respectively. The figure  
361 contains separate plots for the individual measurements from the five field mills used during the  
362 Darwin-2014 campaign, with locations of each numbered field mill detailed in table 3. The decrease  
363 of the electrical field, below  $-2000 \text{ V.m}^{-1}$  is associated with the presence of the cloud. The differences  
364 between the measurements are due to the sensitivity of each field mill to the aircraft potential, the  
365 atmospheric electrical field and the form factor of the aircraft. The methodology described above is  
366 next applied to the data. The time history of the module of the aircraft potential retrieved after the  
367 inversion of equation (2) is plotted in figure 5a, with the IKP2 TWC overlaid. The temporal variations  
368 between the two parameters are strongly correlated.



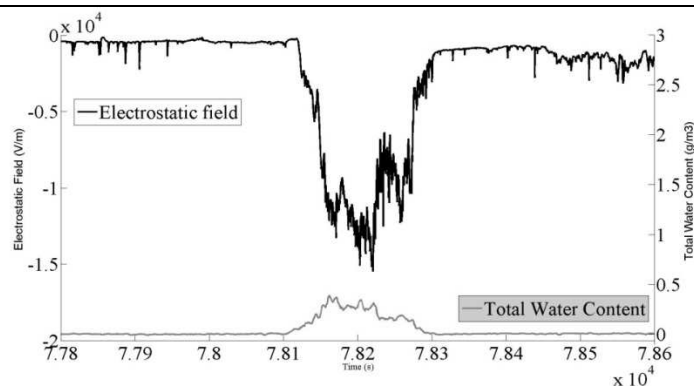
369 **Figure 4 : Measurements from the five field mills of AMPERA system for Flight FS140019 of the Darwin-2014 campaign**  
 370 **(2/9/2014). Each curve represents the measurements of one field mill. Plot E1 (first from the top) is for the field mill on**  
 371 **the rear fuselage. Plots E2 and E3 (second and third from the top), are for the field mills on the left and right windows,**  
 372 **respectively. Plots E4 and E5 (fourth and fifth from the top), respectively E5 (fifth plot for the plot) is for field mill, are for**  
 373 **field mills at the back of PMS probes, on the port and starboard side respectively.**

374 At the beginning of the time sequence, the aircraft flies through an isolated cloud at 11 km AMSL,  
 375 identified by the letter A on figure 5a. A zoomed illustration of the results for cloud A is included in  
 376 figures 5b and 5c. In figure 5b, the recording from the field mill at the back rear fuselage and TWC  
 377 from IKP2 have been plotted. This field mill has been chosen for its relatively high sensitivity to  
 378 electrical potential variation. The comparison of TWC and IKP2 data, plotted in figure 5b, highlights  
 379 the generally good agreement in time evolution when the aircraft flies through an isolated cloud.  
 380 Previous studies have noted that the electric field on the aircraft, recorded by a field mill, may be  
 381 dominated by the aircraft potential (Bateman, 2007; Mach, 2007). In figure 5c, the retrieved aircraft  
 382 potential is plotted with the IKP2 TWC overlaid. Local maxima of TWC are observed at 78160 s, 78190  
 383 s, 78200 s, 78220 s and 78260 s. Maxima are found at the same times in the aircraft potential.  
 384 Moreover, when the TWC is above about  $0.1 \text{ g}\cdot\text{m}^{-3}$ , a significant variation of aircraft potential is  
 385 detected.

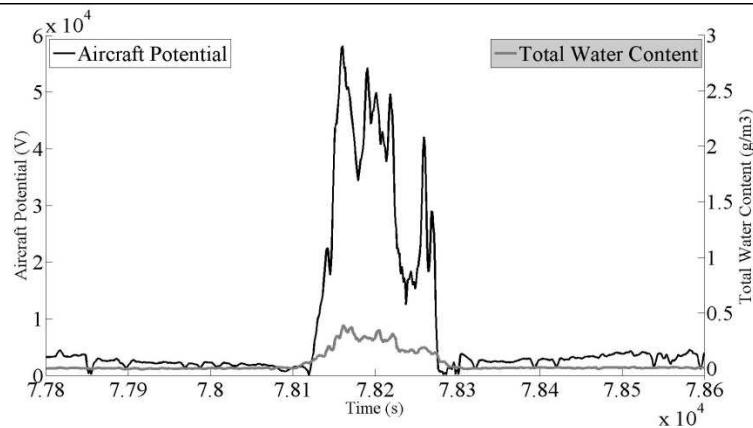
386 The aircraft potential sign is linked to the kind of cloud crossed by the plane. It comes from the  
 387 aircraft charging due to the triboelectric effect. Several authors (Illingworth, 1986; Keith, 1990;  
 388 Laroche, 1986; Tanner, 1961) reported negative charging of metal target impacted by ice crystal; this  
 389 observed in laboratory experiment as well as in flight experiment; whereas droplet observed in warm  
 390 clouds or in mixed-phase region of convective cloud produces a positive charging of the aircraft. In  
 391 this article, our focus was on the time variation of the module of the aircraft potential but not its  
 392 sign.



5a: Time history of the norm of the aircraft potential (black curve- units: V) deduced from AMPERA, and TWC (grey curve – units:  $\text{g}\cdot\text{m}^{-3}$ ) from the IKP2 probe.



5b: Zoomed time history for cloud A identified in figure 5a. Plots are for the electrostatic field ( $\text{V}\cdot\text{m}^{-1}$ ) at the rear fuselage (black curve) and the TWC ( $\text{g}\cdot\text{m}^{-3}$ ) from IKP2 probe (grey curve).



5c: As in figure 5b, but for the norm of the aircraft potential rather than the electrostatic field (black curve). IKP2

393 Figure 5 : Example of field mill and TWC measurements for flight FS14019 (2/9/2014) of the Darwin-2014 campaign from  
 394 HAIC-HIWC project. The top panel (figure 5a) contains cloud measurements from the entire flight, including the time  
 395 evolution of aircraft potential (black curve) in V deduced from the AMPERA system, and the TWC (grey curve) in  $\text{g}\cdot\text{m}^{-3}$   
 396 from IKP2 probe. Time is indicated on x-axis in seconds since UTC midnight. Figures 5b and 5b contain zoomed field mill  
 397 and TWC results from cloud A identified in figure 5a. Figure 5b contains time histories of the electrostatic field results  
 398 ( $\text{V}/\text{m}$ ) for the rear back fuselage field mill (black curve), and TWC from the IKP2 (grey curve). Figure 5c is as in figure 5b,  
 399 but for the aircraft potential (V) rather than the electrostatic field (black curve).

400

401 **4. Results**

402 4.1 Analysis methodology

403 All data from the Darwin-2014 and Cayenne-2015 have been sorted in order to have the same  
404 temporal basis for the IKP probe and AMPERA results and to only use relevant data for our study.

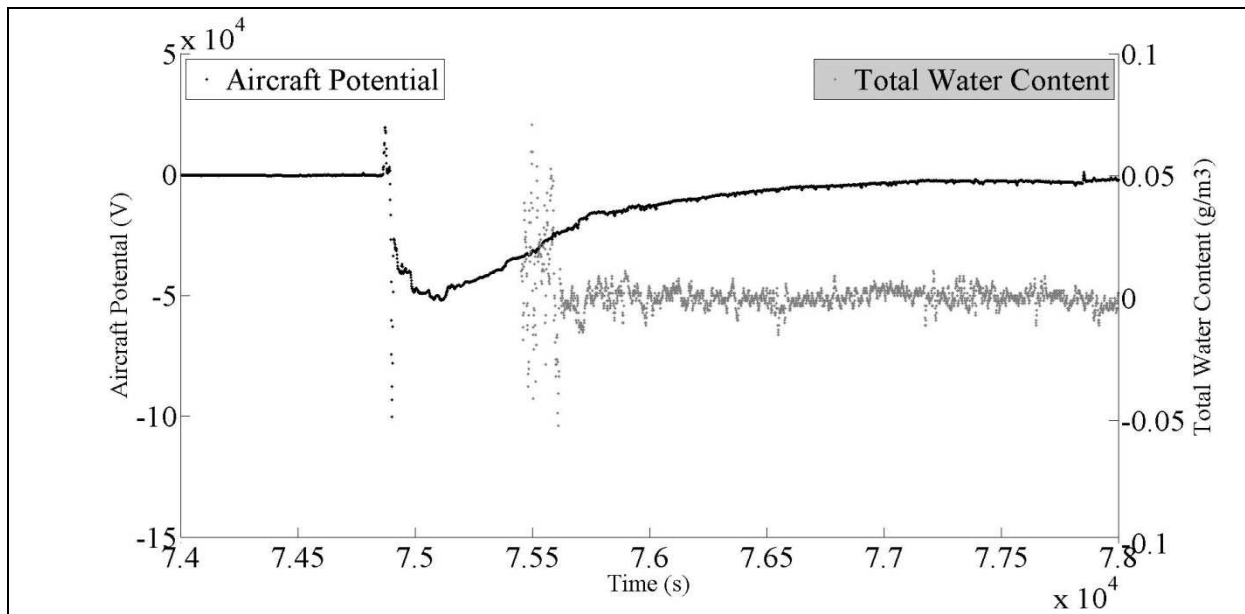
405 In order to calculate the regression coefficient and study the correlation between parameters,  
406 common time-averaging has been used. Due to an observed Licor hygrometer high-frequency  
407 overshoot/undershoot problem in large step changes, IKP2 data have been provided to the HAIC-  
408 HIWC research team as 5-second centered averages at 1 second spacing. The AMPERA system  
409 supplies information on the electrostatic field at a resolution of 100ms. In order to be consistent with  
410 IKP2 time resolution, the same averaging method and scale has been applied to the field mill data.

411 Furthermore, in order to remove the aircraft potential signature, which will not be relevant for this  
412 study, and to take into account the detection limit of the IKP2 probe, data have been sorted based on  
413 the following points for each flight of both campaigns:

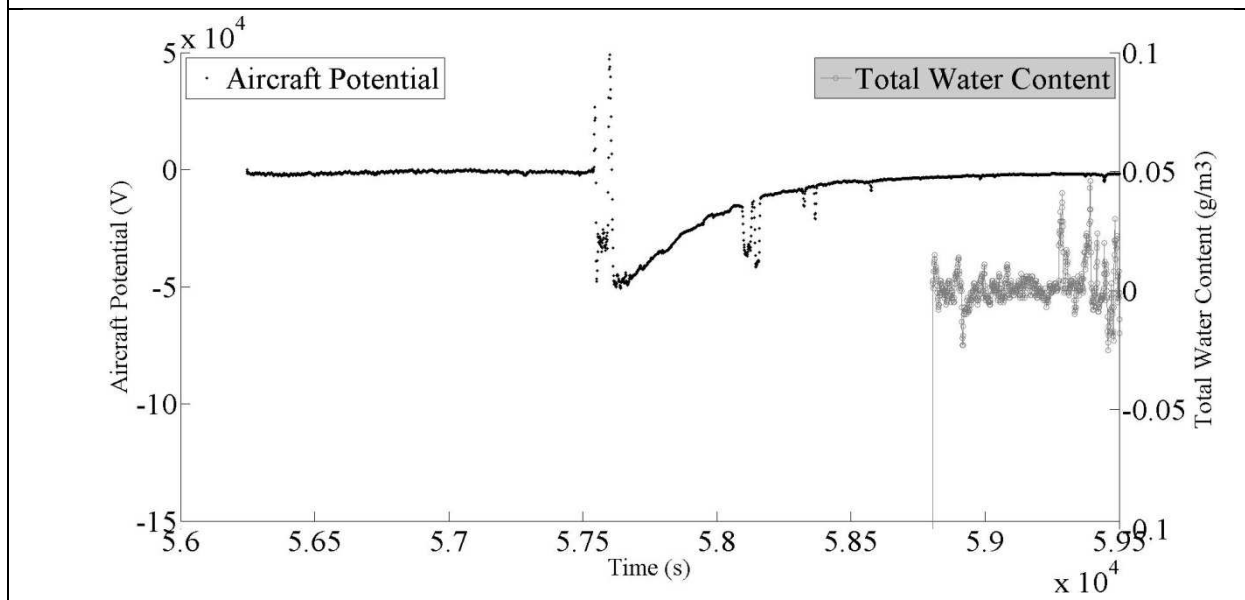
- 414 - Periods when the IKP2 TWC was below  $0.1 \text{ g.m}^{-3}$  have been excluded due to the limitation in  
415 the accuracy of the IKP2 probe at low TWC and the warmer temperatures (Davison et al.  
416 2016, Strapp et al. 2016).
- 417 - Take-off and landing periods have been excluded. During these times, fluctuations in aircraft  
418 potential are dominated by electrostatic charge induced at high power by engine exhaust.  
419 This phenomenon is reproducible from one flight to another. An example of the take-off  
420 period of flight FS140019 (Darwin-2014) and flight FS150015 (Cayenne-2015) is shown in  
421 figure 6. For both flights, the take off period was in fair weather. None of the microphysical  
422 probes detect the presence of TWC. Each plot shows the aircraft potential recorded by the  
423 rear field sensor and the TWC measured by the IKP 2 probe during take-off period. Both plots  
424 reveal a quick decrease of the aircraft potential, followed by a steady signal increase. This  
425 evolution of the aircraft potential is consistent with observations made by Nanevicz (1975).  
426 For these cases, no data before 75540s and 59480s have been used in the statistics  
427 calculations for flights FS14019 and FS150015 respectively.

428





6a - Flight 19 of the Darwin-2014 campaign.



6b - Flight 15 of the Cayenne-2015 campaign.

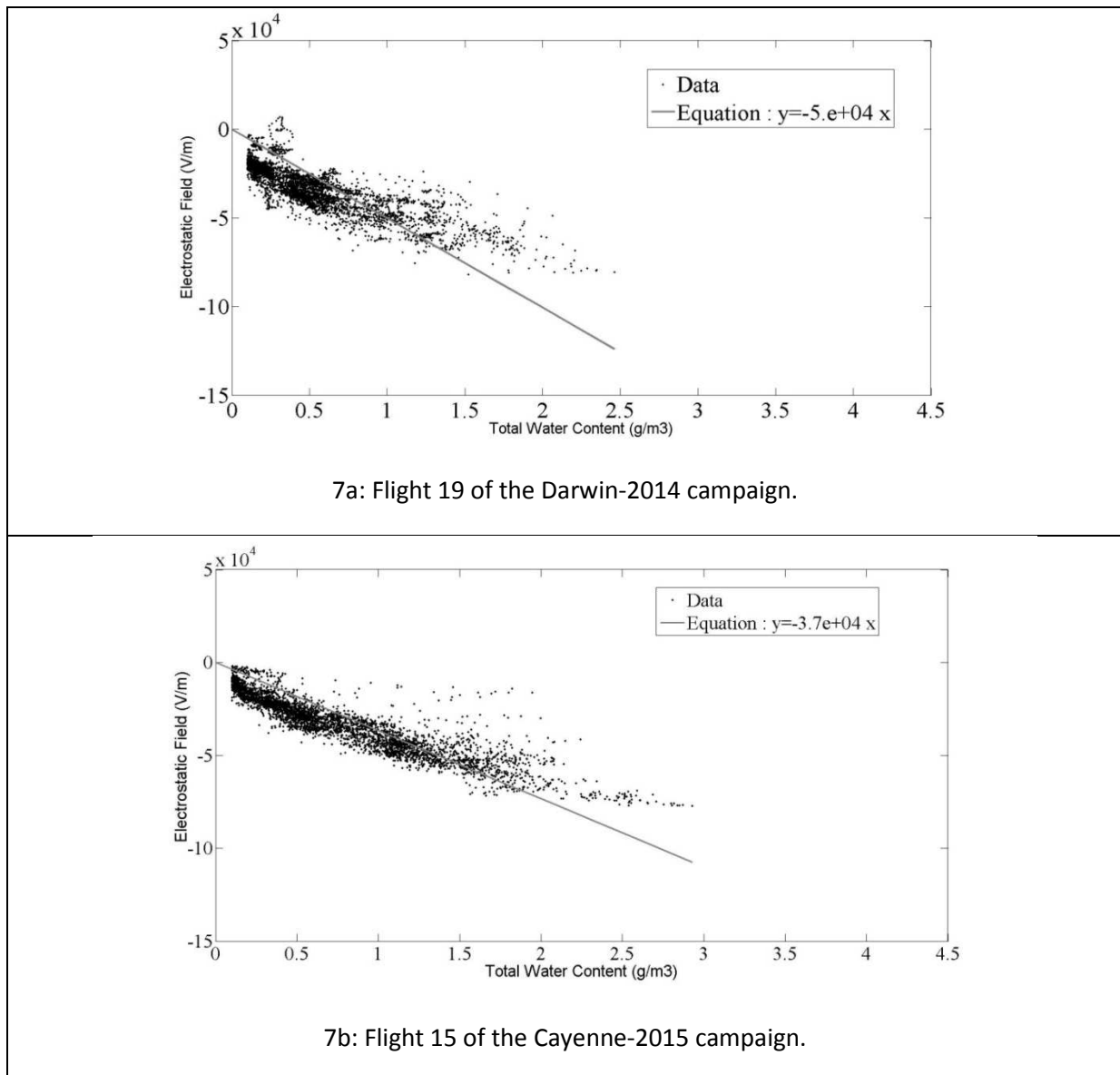
429 **Figure 6 :** Time histories of aircraft potential (V) (black line) and TWC ( $\text{gm}^{-3}$ ) from the IKP2 probe (grey line), for flight 19  
 430 of Darwin-2014 (6a – top panel) and flight 15 of Cayenne-2015 (6b – bottom panel). Time is in seconds from UTC  
 431 midnight.

432 4.2 Comparison between the electrostatic field on the aircraft and the Total Water Content.

433 The previous section has highlighted the general agreement between the time variations of the local  
 434 electrostatic field on the aircraft recorded by the field mill at the rear fuselage on the Falcon 20  
 435 aircraft and the TWC measured with the IKP2 probe, while flying in glaciated clouds at -37 and -47°C.  
 436 When the IKP2 probe detects the presence of ice particles, a correlated response is observed on each  
 437 field mill. Based on this observation, the local electrostatic field measured by the field mill at the rear  
 438 fuselage location has been plotted as a function of the TWC estimated by the IKP2 probe in figures 6

439 (flight 19 of Darwin-2014 and flight 15 of Cayenne-2015) and 7 (Darwin-2014, all data, and Cayenne-  
440 2015 all data).

441 HAIC-HIWC flight campaign clouds were highly dominated by ice crystals (section 1), with only  
442 occasional short mixed-phase cloud with low LWC. The electrostatic field recording from the rear  
443 fuselage field mill for flight 19 of the Darwin-2014 campaign (measurements at two flight levels of -  
444 37°C and -47°C ) and flight 15 of the Cayenne-2015 campaign (measurements at four flight levels of  
445 approximately -35, -22, -12, and -10°C) have been plotted on figure 7. For Darwin-2014 flight 19,  
446 there were no mixed-phase or liquid regions identified. For Cayenne-2015 flight 15, there were a  
447 total of 71 seconds in four brief mixed-phase cloud periods, with maximum period-average cloud  
448 liquid water content of about 0.1 g.m<sup>-3</sup>. The response of the field mills appears to be almost  
449 exclusively associated to ice clouds. For each case, linear regressions of the form  $E_i = \text{coefficient} \times \text{TWC}$   
450 have been fit to the data, and are represented as grey lines on the plots. The characteristics of each  
451 flight and the regression statistics are summarized in table 6.



452 **Figure 7 : Electrostatic field measurements versus TWC for Darwin-2014 flight FS14019 (7a – top panel) and Cayenne-**  
453 **2015 flight FS150015 (7b- bottom panel). Electrostatic measurements (on y-axis – Unit : V.m<sup>-1</sup>) are from the rear back**

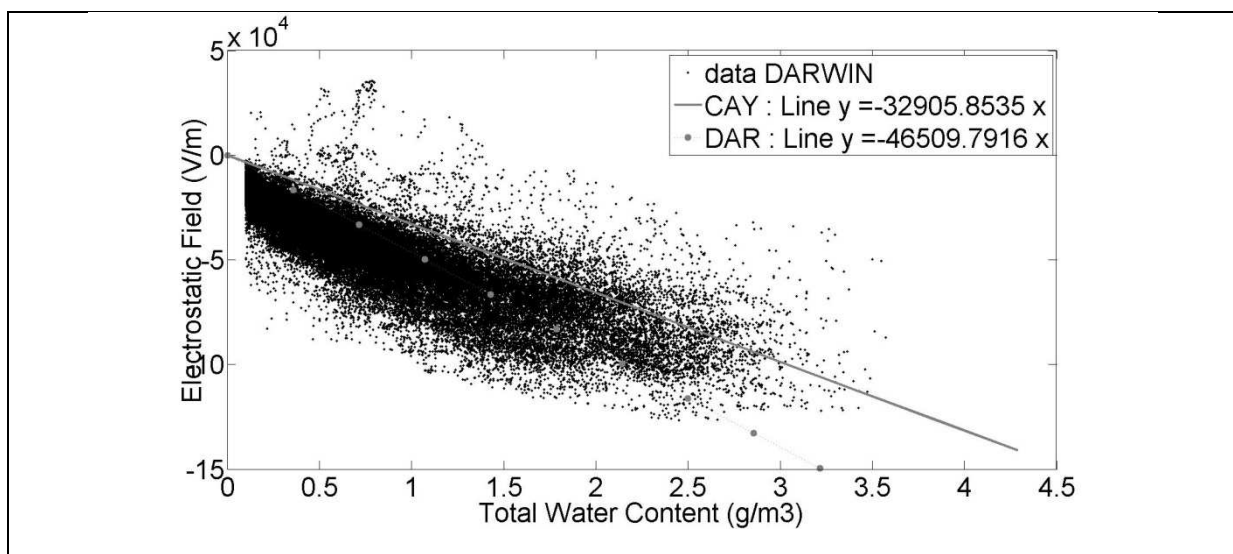
454 fuselage field mill in function of the TWC (on x-axis – Unit:  $\text{g}\cdot\text{m}^{-3}$  - black dots). The linear best fit through the origin is  
 455 shown as the grey line in both plots.

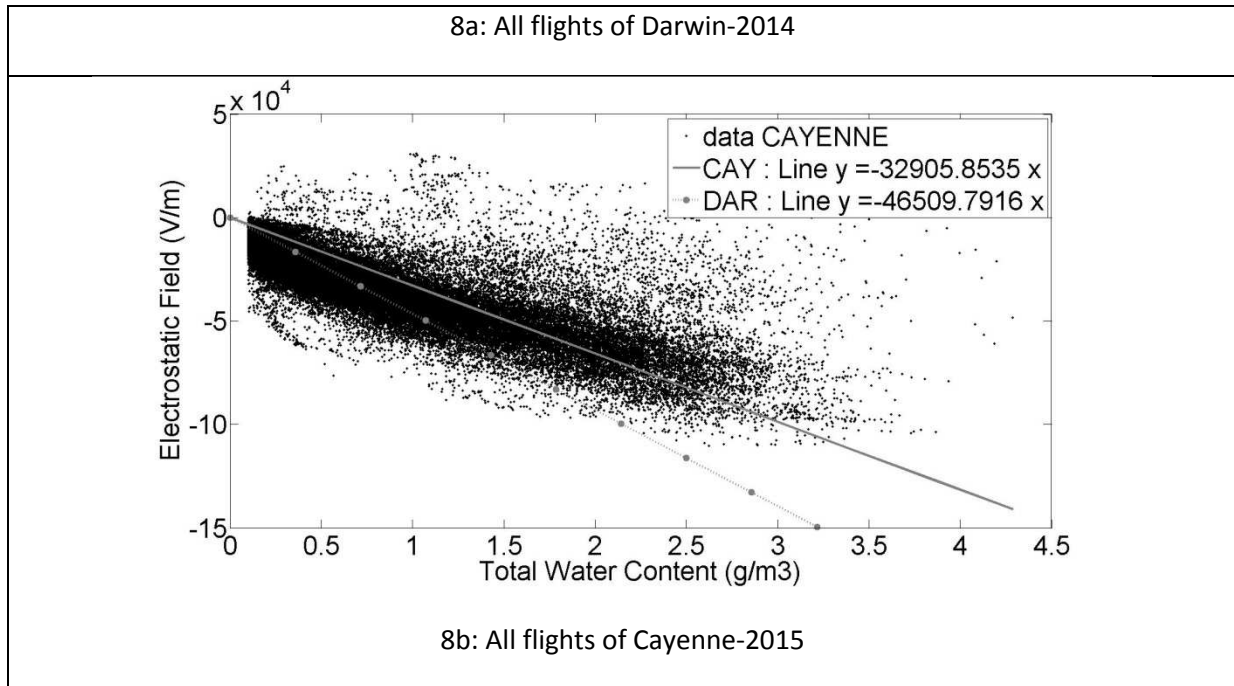
456 Table 6 : Features of flight FS140019 (Darwin-2014) and flight FS150015 (Cayenne-2015).

Information	FS140019	FS150015
Date	02/09/2014	05/16/2015
Take-off/ landing (UTC)	20:48 / 00:14	16:01 / 18:33
Flight altitude (km)	Two flight levels. 11 km and 12.3 km	Around four flight levels. 11 km ; 9 km ; 7.5 km ; 7 km
Temperature ( $^{\circ}\text{C}$ )	-20 , -30	-35, -20, -10
True airspeed ( $\text{ms}^{-1}$ )	185	160-180
TWC maximum ( $\text{gm}^{-3}$ )	3.0	3.5
Regression gain coefficient ( $\text{V/m}/(\text{gm}^{-3})$ )	-50 000	-37 000
Regression Correlation coefficient	0.83	0.91
Number of points for the regression	4 224	4 053

457

458 Results deduced from sixteen Darwin-2014 and sixteen Cayenne-2015 flights are plotted in figure 8,  
 459 which includes linear regressions represented in the grey curves as in figure 7. Further information  
 460 on these flights is given in table 7. The gain of the linear regressions is  $47000 (\text{V/m})/(\text{g}\cdot\text{m}^{-3})$  for  
 461 Darwin-2014, and  $33000 (\text{V/m})/(\text{g}\cdot\text{m}^{-3})$  for Cayenne-2015.





462 **Figure 8 :** Same as figure 6 for all flights of Darwin-2014 (8a - top panel) and Cayenne-2015 (8b - bottom panel). The linear  
 463 best fit through the origin is shown as the grey line in both plots.

464 In order to estimate the dispersion of these results, separate fits have been derived for each  
 465 individual flight. A mean value and a standard deviation based on the results for each flight, has been  
 466 calculated and compared to the gain found with all campaign flights. For the Darwin-2014 campaign,  
 467 the mean of the individual gain coefficients is 50 000, which is similar to the overall gain of 47 000  
 468 (V/m)/(g·m<sup>-3</sup>). Similar results were found for the Cayenne-2015 campaign. For both campaigns, the  
 469 standard deviation is small. The Darwin-2014 and Cayenne-2015 correlation coefficients for all flights  
 470 are also include in table 7, both being about 0.8, and confirming a good correlation between the  
 471 electric field and TWC. Within each campaign, the relationship between the electric field and the  
 472 TWC seems reasonably reproducible. However, there is clearly a stronger electric field response to  
 473 clouds in Darwin-2014 than in Cayenne-2015, an observation that will be discussed further below.  
 474 The Cayenne gain coefficient is approximately 32% lower than that for Darwin. Furthermore, for a  
 475 given TWC, there is a fairly large scatter in the possible electrostatic field values. This is at least  
 476 partially due the expected scatter in the IKP2 due to the assumption of ice saturation BWV, and also  
 477 due to the very large differences in the sample volumes of the two parameters.

478 **Table 7 :** Statistics on electrostatic field versus TWC for both campaigns.

	Darwin-2014	Cayenne-2015
Number of flights used	16	16
(noted Nb)		
Mean of individual gain coefficients (Nb flights) (V/m)/(g·m <sup>-3</sup> )	-50 000	-34 000
Standard deviation on Nb flights	7 000	6 000

(V/m)/(g.m <sup>-3</sup> )		
Number of point in the statistics	70 000	80 000
Gain coefficient estimated using all data from Nb flights (V/m)/(g.m <sup>-3</sup> )	-47 000	-33 000
Correlation coefficient on the Nb flights	0.86	0.83
Conclusion	$E_{SA} \sim -47\,000 \times TWC$	$E_{SA} \sim -34\,000 \times TWC$
TWC maximum (g.m <sup>-3</sup> )	3.57	4.29
TWC mean (g.m <sup>-3</sup> )	0.74	0.74
Standard deviation (g.m <sup>-3</sup> )	0.6	0.7

479

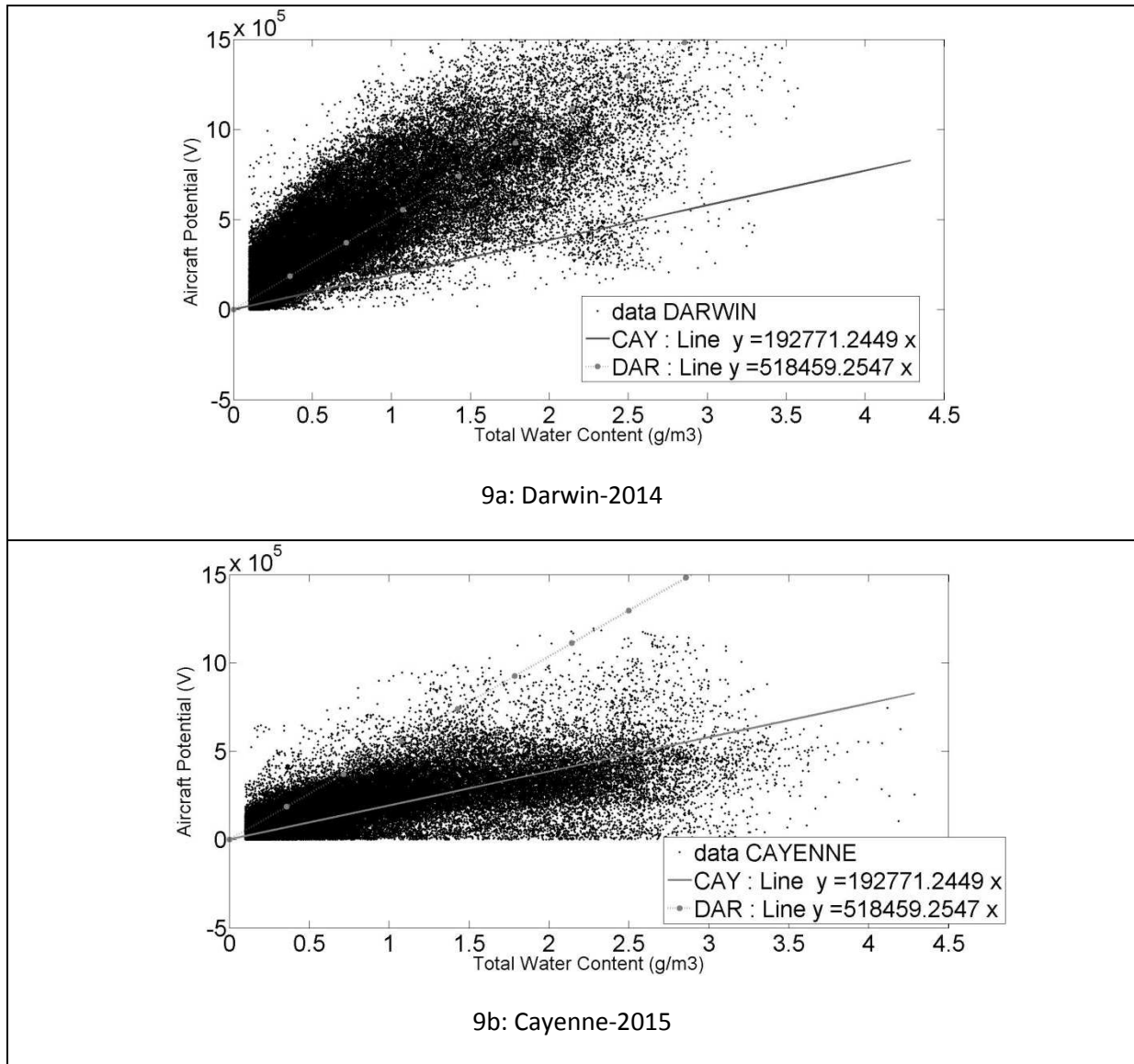
480

#### 4.3 Comparison between the aircraft potential and the Total Water Content.

481

The magnitude and variation of the electrostatic field on the aircraft skin depends on the atmospheric electrostatic field around the aircraft and the net electric charge of the aircraft. This latter depends on the balance current on the aircraft fuselage and is tied to the particle concentration. Indeed, charge will mainly accumulate on the aircraft by the triboelectric effect and by the engine exhaust. This accumulation will induce an increase of the aircraft potential. It is assumed here that the aircraft potential variation comes mainly from the triboelectric effect and the corona effect. As in section 4a, statistics have been calculated following the same principle, but this time for the module of the aircraft potential versus TWC. Figure 9 contains results from all flights of Darwin-2014 (9a) and Cayenne-2015 (9b). The grey line on the figures represents the linear regression fit for each dataset. The gain coefficient is 520 000 V/(gm<sup>-3</sup>) for Darwin-2014 and 190 000 V/(gm<sup>-3</sup>) for Cayenne-2015. The mean and standard deviation of the TWCs obtained from the flights of each campaign are similar. The correlation coefficients for all flights, by campaign, are 0.8 for Darwin-14 and 0.7 for Cayenne-2015.

493



494 **Figure 9 : Module of the aircraft potential versus TWC, for Darwin-2014 (9a-top panel), and Cayenne-**  
 495 **2015 (9b-bottom panel). Data are from all flight described in table 7. The linear best fit through the origin is shown as the grey line in both**  
 496 **plots**

497 Finally, if we merge the information from all flights of both campaigns (Darwin-2014 and Cayenne-  
 498 2015), an overall gain coefficient and correlation coefficient is found between the aircraft potential  
 499 and the TWC. Based on this result, we can establish the following general relationship:

500 
$$V_a = g * TWC \quad (4)$$

501 where  $V_a$  is the aircraft potential, TWC is the total water content and  $g$  is the regression gain  
 502 parameter. As in the previous section for electrostatic field, there is a fairly large scatter in expected  
 503 aircraft potential for a given TWC.

504 The quantiles (15 %, 50 % and 85 %) of aircraft potential for each  $0.2 \text{ g.m}^{-3}$  TWC interval have been  
 505 calculated to complete the results shown on figures 9. Results are plotted in figure 10 for both  
 506 campaigns (Darwin-2014 in black lines and Cayenne-2015 in grey lines). This plot highlights the  
 507 differences between the two campaigns and quantifies the variability of results within a campaign.

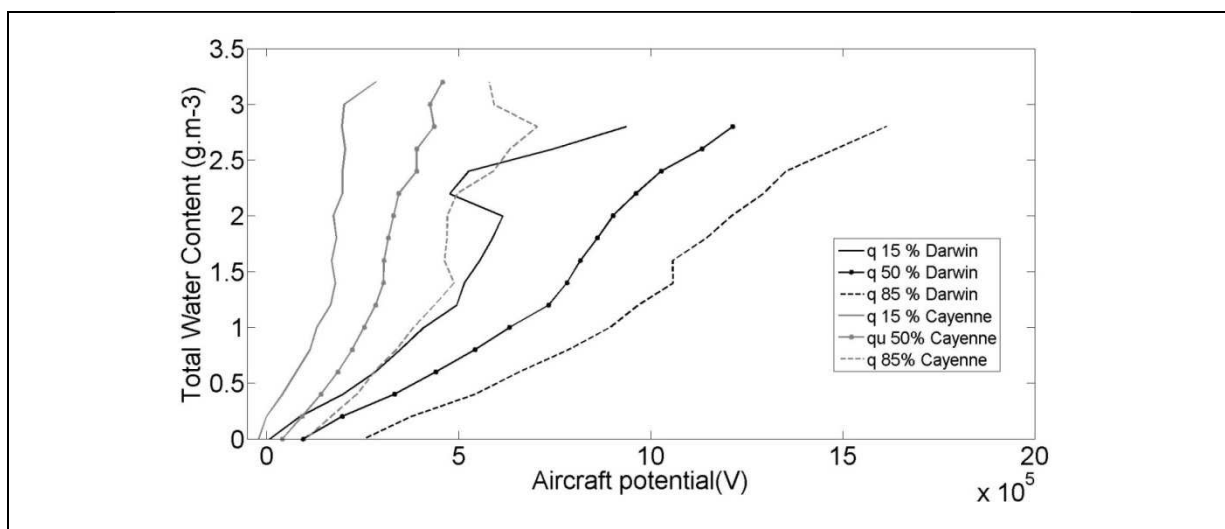
508 For each campaign, for a fixed aircraft potential, the range of observed TWC values is very large. For  
 509 example, for Darwin-2014, the 15-85% quantile TWCs for a 500kV are 0.5 to 1.5 g.m<sup>-3</sup>. For Cayenne-  
 510 2015, this 500kV is reached 15% of time only for TWCs greater than about 2.25 g.m<sup>-3</sup>.

511 The wide range of IWC values for a given aircraft potential, within a campaign, could in part be  
 512 explained by scatter in the IKP2 measurements and sample volume differences. However, this cannot  
 513 explain the overall scale differences of the aircraft potential response to TWC observed between the  
 514 two campaigns.

515 At 1.5 g.m<sup>-3</sup>, the 15-85 % quantile aircraft potential is 100 - 500 kV for Cayenne-2015 versus 500-1000  
 516 kV for Darwin-2014.

517 In spite of the fact that a similar distribution of TWC values was observed in both campaigns, only a  
 518 small percentage of aircraft potential values greater than 500 kV, was found in Cayenne-2015, where  
 519 such values were common in the Darwin-2014 data.

520 The form of equation (4) implies that outside cloud, in fair weather conditions, the aircraft potential  
 521 should be zero. In real flight condition, others effects than those inducing by particles collisions must  
 522 be taken into account. Indeed, the corona effect or the engine exhaust (as illustrated before with  
 523 figures 6) would be considered. Concerning the Falcon 20 aircraft potential due to engine charging,  
 524 Figure 6 shows that this charging effect occurred from take-off to about 11 km altitude; the  
 525 maximum effect is observed around 4 km altitude (Va ~ -50 kV); then, as the aircraft altitude  
 526 increases, the potential magnitude decreases and reaches a value as low as 2 kV, closed to the  
 527 AMPERA network threshold. When the aircraft is flying inside iced clouds, its potential reaches  
 528 hundreds of kV, a magnitude much larger than the network threshold.



529 **Figure 10 : Quantiles of aircraft potential in 0.2 gm<sup>-3</sup> TWC intervals (Darwin-2014 black, Cayenne-2015 grey). The quantile**  
 530 **15% is in solid line; the quantile 50% is in solid line with circle and the quantile 85 % is in dashed line. Aircraft potential**  
 531 **on x-axis (Unit : V). Total Water content on y-axis. (Unit : g.m<sup>-3</sup>).**

532 Figure 10 underscores the limitation of our methodology in estimating TWC. Despite these  
 533 limitations, the collective data from all flights of both campaigns has consistently established a  
 534 relationship between the aircraft potential and the IWC for every flight. In its current state of  
 535 development, the methodology gives a realistic estimation of TWC.

536



537 **5. Discussion**

538 5.1 Relationship between the total water content and the aircraft potential.

539 The starting point in understanding equation 4 and in defining parameters related to the gain  
540 parameter  $g$ , lies in the electrical charging and discharging processes of the aircraft during flight. A  
541 cloud is composed of multiple hydrometeors. During the HAIC-HIWC campaign, the aircraft flew  
542 through convective cloud dominated by ice particles that impacted the fuselage of the aircraft.  
543 These impacts led to electrical charge exchanges between the aircraft fuselage and the particles by  
544 the triboelectric effect. It produced a charging process equivalent to a charge current (the charge  
545 current is noted  $I_c$ ). This charging phenomenon is a known process, observed by Nanevicz and Tanner  
546 (1961, 1974), Boulay and Laroche (1982), and Laroche (1985). From 1940 to 1980, the phenomenon  
547 was noted as a source of radio-electric disturbance for navigational systems (Stimmel, 1946). The  
548 mitigation of this phenomenon consists of installing passive potential dischargers for corona  
549 discharge, which act to decrease the aircraft potential. Many measurement campaigns have been  
550 conducted worldwide to study electrical parameters during aircraft flight. These campaigns have  
551 revealed that the charge ( $Q$ ) transferred by impact of a hydrometeor on the aircraft fuselage was on  
552 the average 10 to 20pC (Tanner, 1961; Nanevicz, 1974; Illingsworth, 1986). The amount of the charge  
553 deposited on the aircraft varied considerably from cloud to cloud and even from particle to particle  
554 in the same cloud (Tanner, 1961). The amount appeared to be a function of the aircraft speed  
555 (Illingsworth, 1986; Tanner, 1961), the shape and the size of the particles and environmental  
556 parameters such as the temperature (Saunders, 2004).

557 The intensity of the charging current ( $I_c$ ) is proportional to the product of the average particle charge  
558 transferred at each collision and the number of particles striking the aircraft per unit of time. This  
559 second parameter is proportional to the particle concentration ( $N$ ) in cloud, the aircraft speed ( $V_p$ )  
560 and the effective impact surface of impingement ( $S_{eff}$ ; Tanner, 1961). The charging current increases  
561 the net electrical charge of the aircraft and the aircraft potential (Illingsworth, 1986; Larigaldie, 1980;  
562 Boulay, 1982). The expression for the charging current is given by:

563 
$$I_c = V_p * S_{eff} * Q * N \quad (5)$$

564 The increase of the aircraft potential is limited by the ignition of electrical corona discharges from the  
565 sharpest points of the aircraft. A corona discharge initiates when the electrical field on the aircraft  
566 skin reaches the air breakdown field (Boulay, 1982). The discharge current ( $I_d$ ) associated with the  
567 corona depends on the aircraft potential ( $V_a$ ), the air density and the aircraft geometry. Using a first  
568 order approximation, the corona current can be represented by equation (5) below, with  $k$  being a  
569 scale coefficient. As mentioned in Boulay (1982), the temperature, pressure and the aircraft  
570 geometry play important roles on the manifestation of the discharged current, and more precisely in  
571 the  $k$  coefficient.

572 
$$I_d = k * V_a \quad (6)$$

573 In Boulay and Laroche (1982), a Gloster Meteor aircraft (with a cross-section of 8.32 m<sup>2</sup>) was  
574 instrumented with field mills sensors, triboelectric current measurement on instrumented dielectric  
575 panel. The aircraft was flown in various atmospheric conditions. As part of their results, they  
576 measured the discharge current as a function of the aircraft potential. Based on these results, the  $k$



577 coefficient for an aircraft of this size and a potential of approximately 100 kV, flying at 200m.s<sup>-1</sup>, was  
 578 estimated at 400 μA.kV<sup>-1</sup>.

579 The variation of the aircraft potential V<sub>a</sub> is given by the following relationship:

$$580 \quad V_a(t) = \frac{1}{C_a} \int_0^t (I_c - I_d(V_a, \dots)) du \quad (7)$$

581 The relationship between charging and discharging current is obtained by taking the time derivative  
 582 of equation (7),

$$583 \quad I_c = I_d + C_a \frac{dV_a}{dt} \quad (8)$$

584 Calculation of the displacement current ( $C_a \frac{dV_a}{dt}$ ) shows that this parameter remains small compared  
 585 to the charging and discharging current. If the charge equilibrium is reached quickly relative to the  
 586 time variation of the measurement, a steady state can be assumed leading to:

$$587 \quad I_c = I_d(kV_a, \dots) \quad (9)$$

588 Based on the assumption of the electrostatic equilibrium (equation 9) and using approximations  
 589 detailed previously for the charging current (equation 5) and the discharging current (equation 6), the  
 590 aircraft potential can be linked to the particle concentration N by the following formula:

$$591 \quad N = \frac{(k*V_a)}{V_p(z) \times Q(Dm, \text{class of hydrometeor}) \times S_{eff}(Dm, S_a)} \quad (10)$$

592 where V<sub>p</sub> is the aircraft velocity (typically a function of altitude during flight); Q, the charge  
 593 transferred by collision (a function of the median diameter, D<sub>m</sub>, and class of hydrometeors); S<sub>eff</sub>, the  
 594 effective impingement surface (dependent on the impingement coefficient, the size of particles and  
 595 the aircraft cross-sectional area); k, the correlation scale parameter; C<sub>a</sub>, the aircraft capacitance and  
 596 V<sub>a</sub>, the aircraft potential. The implicit assumption associated with equation (9) is that the charging  
 597 conditions are representative of the average conditions existing on all the aircraft surfaces.

598 TWC can be estimated from the particle concentration, N (detailed in equation 10), taking into  
 599 account the particle size distribution. In the section 4, it was contended that aircraft potential and  
 600 TWC were related through a linear coefficient g (equation 4). Based on equation 10, the parameters  
 601 determining g can be defined. The coefficient g depends mainly on the particle charge transferred at  
 602 each collision, the effective impingement surface, the aircraft velocity, the aircraft electrical  
 603 capacitance, and the particle diameter (D<sub>m</sub>). A more detailed relationship between the TWC and the  
 604 aircraft potential can be formulated as follows:

$$605 \quad V_a = g \left( N, Q, S_{eff}, V_p, C_a, D_m, \frac{1}{k} \right) \times TWC(D_m, N) \quad (11)$$

606 **5.2 Discussion of the difference of correlation gain coefficient found between the two**  
 607 **campaigns.**

608 In section 4, the aircraft potential, inferred from the electric field measurements recorded by the  
 609 field mills was compared to the independently measured TWC. Linear fits between these parameters  
 610 highlighted a strong positive correlation, with dependent factors that are described in equation (11).

611 Based on the equation (11) and the flight conditions met during the Darwin-2014 and Cayenne-2015  
612 campaigns, investigations have been conducted in order to try to explain the difference in terms of  
613 gain coefficient discussed in section 4.

614 During the Darwin-2014 and Cayenne-2015 campaigns, the same Falcon-20 aircraft with the same  
615 probe configuration was used. Consequently, of those parameters listed in equation (11), the  
616 effective impingement surface ( $S_{eff}$ ), the aircraft speed ( $V_p$ ) and the aircraft capacitance ( $C_a$ ) are the  
617 same for both measurements campaigns. The aircraft true airspeed was about  $190 \text{ m}\cdot\text{s}^{-1}$  during each  
618 flight of the Darwin and Cayenne campaigns. The aircraft capacitance deduced from the Poisson  
619 calculations for the Falcon-20 mesh, was around 500 pF.

620 The effective intercepting area of the aircraft, i.e. the cross-sectional area of the aircraft weighted by  
621 the impingement coefficient, is typically 60% of the aircraft projected frontal area (Tanner, 1961). For  
622 the Falcon 20 aircraft, the cross-sectional area is  $12.3 \text{ m}^2$ . The impingement coefficient depends on  
623 the size of particles and a capture coefficient. This coefficient reflects that the larger particles (larger  
624 than  $50 \text{ }\mu\text{m}$ ) have more chance to impact the fuselage because of their ballistic trajectory. In  
625 contrast, smaller particles tend to be diverted away by the airflow streamlines (Tanner, 1961).  
626 Experimental investigations have been performed on the impingement efficiencies, taking into  
627 account cloud parameters such as the LWC, the size of particles, aerodynamic characteristics such as  
628 the airfoil shape and the angle of attack (Papadakis, 2000). Examples of the magnitudes of  
629 impingement efficiencies and the link to particle size have been given in Papadakis (2000), who found  
630 impingement efficiencies of 0.4, 0.6 and 0.7 for particles with  $11.5 \text{ }\mu\text{m}$ ,  $21 \text{ }\mu\text{m}$  and  $92 \text{ }\mu\text{m}$  median  
631 volumetric diameters respectively.

632 As mentioned before, the impingement coefficient but also the charges of the particles depend on  
633 the particles spectra dimension. Equation (11), deduced from equation (4), formulates a linear  
634 relationship between  $V_a$  and TWC but does not demonstrate it: if  $N$ , the concentration of cloud  
635 particles can be considered as producing a mean elementary charge  $Q$ , with a mean effective impact  
636 area  $S_{eff}$ , then the charging current  $I_c$  can be described by equation (5). It is important to take into  
637 account the whole spectra of particles. The relationship put in advance in this article comes from the  
638 best fit between the two set of data. We do not propose a rational to predict a simple linear  
639 relationship between potential and TWC.

640 Other parameters such as the aircraft accelerations, wind direction, wind speed and internal  
641 parameters of the field mill (temperature, motor current) have been compared. These parameters  
642 were similar during both campaigns.

643 The difference in the magnitude of the regression gain coefficient,  $g$ , could possibly be explained by  
644 differing meteorological conditions. During both campaigns, similar MCSs were sampled at a variety  
645 of altitudes. Consequently, it is contended here that gain coefficient differences between the two  
646 campaigns might be explained by differences in the particle size distribution and/or the atmospheric  
647 conditions (temperature and pressure), which play a role in the charging of the aircraft through the  
648 tribo-electric effect and the discharging through the  $k$  coefficient.

649 The aircraft configuration and maintenance have also been checked in order to understand the gain  
650 differences between Darwin-2014 and Cayenne-2015 campaigns. Between both campaigns, the  
651 aircraft and probes configuration on the Falcon 20 aircraft have been the same. Nevertheless,

652 changes on aircraft maintenance occurred before the beginning of the Cayenne-2015 campaign.  
653 Among them, the painting and the static wings on the nose of the plane have changed. These  
654 changes may have an impact on the charging (for the painting) or the discharging (for the static  
655 wings) of the aircraft.

### 656 The Influence of temperature

657 There were some differences in the flight environments between Darwin-2014 and the Cayenne-  
658 2015 campaigns. The former campaign collected data primarily in the -30 and -40°C temperature  
659 intervals, while the latter additionally focused on the -10 and -50 temperature intervals in order to  
660 achieve the desired HAIC-HIWC data collection at all 4 temperature intervals. The higher occurrence  
661 of mixed-phase clouds in Cayenne (section 1), although still rare, may have contributed somewhat to  
662 differences in the particle microphysical characteristics, for example for dense particles due to  
663 riming. Furthermore, the differences in the temperature levels flown in the two campaigns may have  
664 contributed to net differences in the atmospheric pressure and true airspeed that could affect  
665 equation (11), although the campaign differences were not abundantly different. Perhaps the most  
666 notable difference in Cayenne-2015 was the large fraction of data from the -10°C level. Leroy et al.  
667 (2017) have shown that the median mass diameter (MMD) of particles increased significantly with  
668 temperature, implying that the Cayenne-2015 dataset could be composed of particle collectively  
669 larger than Darwin-2014.

670 The impact of the air temperature and consequently the pressure and altitude are exemplified  
671 through the study of Cayenne-2015 flight 13 (FS150013) and based on statistics from all flights. Time  
672 history measurements of flight 13 (05/18/2015) are shown in the four panels of figure 11, including  
673 aircraft potential (top left), TWC (top right), altitude (bottom left), and static air temperature (bottom  
674 right). During this flight, the aircraft flew at three different level (approximately 7 km, 10 km and 12  
675 km), corresponding to approximately -10°C, -30°C and -45°C in air temperature. The magnitude and  
676 the fluctuations of the retrieved aircraft potential do not seem to be linked to the changes of air  
677 temperature. This point is further supported by the following analysis. TWC and aircraft potential  
678 measurements have been sorted into three 10°C intervals, centered on -20°C, -30°C, and -40°C. Then  
679 quantiles (15 %, 50 % and 85 %) of aircraft potential have been calculated for each  $0.2 \text{ g}\cdot\text{m}^{-3}$  TWC  
680 interval. Results are presented for -20, -30, and -40°C in figures 11b-11d respectively. On each figure,  
681 Darwin-2014 and Cayenne-2015 results are shown as black and grey curves. The numbers of points  
682 used for the statistics for each campaign are contained in figures 11e and 11f. Note that the Darwin-  
683 2014 aircraft potential results are consistently higher than Cayenne-2015 for all temperature  
684 intervals. Furthermore, there is no obvious change in the magnitude of the aircraft potential for the  
685 same TWC with changes in temperature for either campaign. These results suggest that the pressure  
686 level, and consequently the temperature and altitude have no obvious impact on the linear  
687 regression gain coefficient between the aircraft potential and the TWC, obtained for both campaigns.  
688 Variations of temperature and pressure cannot alone explain the gain difference in aircraft potential  
689 versus TWC observed between the two campaigns.

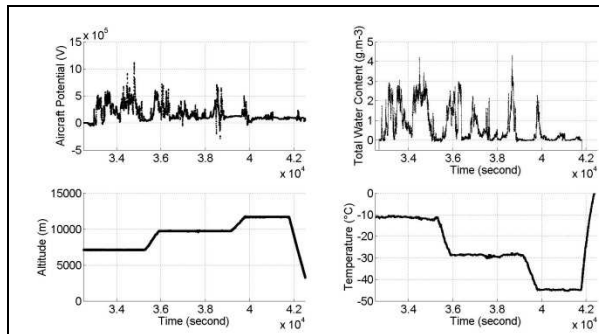


Figure 11a. Flight 150013 of Cayenne.

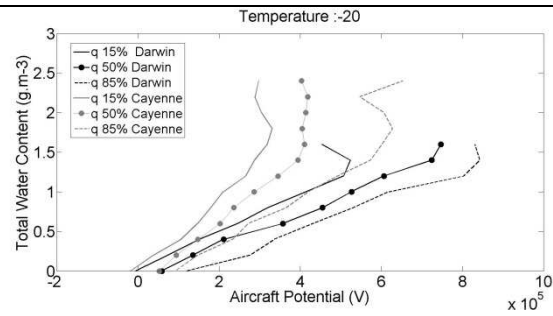


Figure 11b. Quantile. Gap of temperature centered at  $-20^{\circ}\text{C}$ .

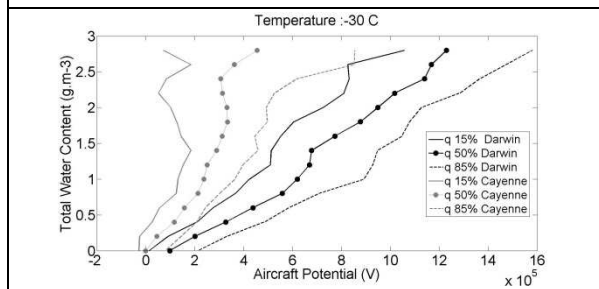


Figure 11c. Quantile. Gap of temperature centered at  $-30^{\circ}\text{C}$ .

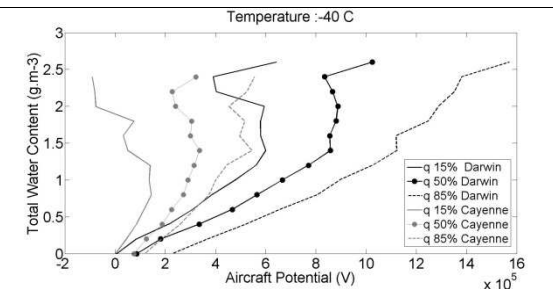


Figure 11d: Quantile. Gap of temperature centered at  $-40^{\circ}\text{C}$ .

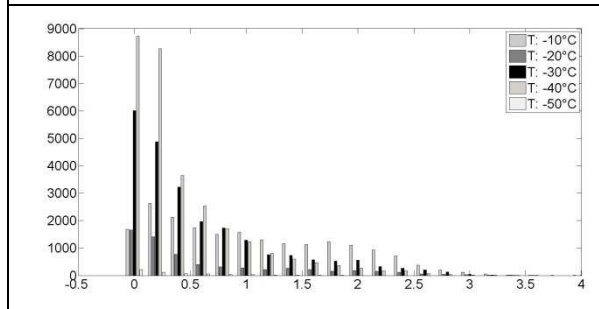


Figure 11e : Number of point used for the statistics. Cayenne-2015.

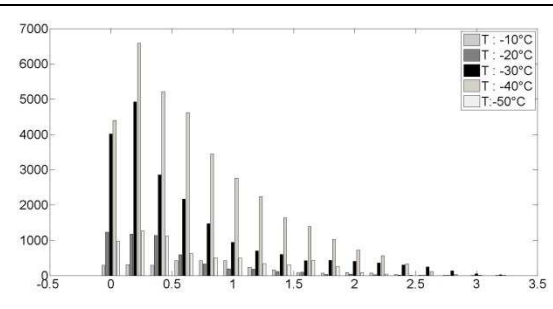


Figure 11f : Number of point used for the statistics. Darwin-2014.

690 Figures 11(a-f) : (a) Time histories of the aircraft potential (top left), the TWC (top right), the altitude (bottom left), and  
 691 the temperature (bottom right), for flight FS150013 of the Cayenne-2015 campaign; (b) quantiles of aircraft potential in  
 692  $0.2 \text{ gm}^{-3}$  TWC intervals (Darwin-2014 black, Cayenne-2015 grey), for the  $-20 \text{ C}$  temperature interval; (c) as in (b) but for  
 693 the  $-30 \text{ C}$  temperature intervals; (d) as in (b) for the  $-40 \text{ C}$  temperature interval; (e) number of points used in the  
 694 Cayenne-2015 statistics, and (f) number of points used in the Darwin-2014 statistics. Times in (a) are seconds after UTC  
 695 midnight. Quantiles for (b), (c), and (d) as follows: (15% in solid line, 50% in solid line with circle, 85% in dashed line).

696 The reason for the gain differences between the electric field measurements versus TWC during  
 697 Darwin-2014 and Cayenne-2015 remain an unresolved question. There is nothing in the IKP2 TWC  
 698 measurements to suggest an overall TWC scale factor difference between the two campaigns. The  
 699 statistics of the IKP2 TWC measurements in Cayenne-2015 were similar to those of Darwin-2014,  
 700 with Cayenne-2015 TWCs in fact being a little higher than those of Darwin-2014, in the opposite  
 701 direction as that required to explain the higher aircraft potential readings in Darwin-2014. An overall  
 702 30 % TWC measurement error between Darwin and Cayenne is not considered possible. Further  
 703 work is required to investigate other possible influences. Ice particle properties such as morphology,

704 and PSD bulk properties such as median and other percentile mass diameters may have an effect on  
705 the charge transfer on impact with the fuselage.

## 706 **6. Conclusions**

707 During the HAIC-HIWC campaign, airborne instrumentation including microphysical probes and  
708 electric field probes have been used to sample mostly glaciated high TWC convective cloud with only  
709 rare occurrences of mixed-phase. The data were collected during the Darwin-2014 and the Cayenne-  
710 2015 flight campaigns. The comparison of data recorded by a network of field mills installed flush on  
711 the aircraft fuselage (the AMPERA system) and on PMS canisters under the aircraft wings, and the  
712 TWC estimated by the IKP2 probe revealed a good agreement in terms of temporal variation.  
713 Statistical analysis confirmed the good correlation between the aircraft potential and the TWC. The  
714 linear regression gain and correlation coefficients for a fit through the origin have been calculated for  
715 each flight of each measurement campaign. Gain coefficients ( $V$  per  $gm^{-3}$ ) were similar from one flight  
716 to another within the same measurement campaign, but were about 63% lower for Cayenne relative  
717 to Darwin. It was speculated that the main impact affecting the gain difference could come from the  
718 particle size distribution (morphology, median mass diameter etc.) and possibly the temperature.

719 Based on these results, a new approach for estimating TWC is proposed based on the data delivered  
720 by the AMPERA system, and using the empirical gain coefficients derived from the HAIC-HIWC  
721 dataset. Through this new approach, the whole aircraft acts as the sensor. Thus, for flights with the  
722 same type of aircraft and the same AMPERA configuration, the coefficients reported here could be  
723 applied as a first-order approximation for estimating TWC from the aircraft potential. Nevertheless,  
724 the methodology does not allow obtaining an IWC value at a high degree of accuracy. This method  
725 would be useful for real-time detection on commercial aircraft as a first guess for TWC. This new  
726 concept could deliver a first order of IWC conditions and provide a warning to pilots of commercial  
727 aircraft.

728 This study has brought evidence of the relationship between the electrical potential and the total  
729 water content. Future studies have to be performed in order to analyse the correlation between the  
730 aircraft electrical charging and microphysical parameters as the size spectrum of the impacting cloud  
731 particles or the properties of ice crystals and the aerosol types.

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