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ON ERROR SOURCES DURING AIRBORNE MEASUREMENTS OF THE AMBIENT ELECTRIC FIELD

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ABSTRACT

The paper addresses the principal sources of errors during airborne measurements of the ambient electric field and charge. Results of their analysis are presented for critical survey. It is demonstrated that the volume electric charge has to be accounted for during such measurements, that charge being generated at the airframe and wing surface by droplets of clouds and precipitation colliding with the aircraft. The local effect of that space charge depends on the flight regime (air speed, altitude, particle size and cloud elevation). Such a dependence is displayed in the relation between the collector conductivity of the aircraft discharging circuit - on the one hand, and the sum of all the residual conductivities contributing to aircraft discharge - on the other.

Arguments are given in favour of variability in the aircraft electric capacitance. Techniques are suggested for measuring from factors to describe the aircraft charge.

INTRODUCTION

During last years many experts sought for objective estimates of the ambient electric field (**E**) measurement accuracy, and of a similar characteristics for the aircraft electric charge, **Q**. That aircraft is envisaged as a platform outfitted with a measurement system of several field mills.

Interest in the physical processes of cloud electrification, in the conditions for generation of both the natural and triggered lightning discharge, in the physical processes of electrification of flying vehicles, and in the dependence of such processes on the properties of environment and the vehicles themselves all stimulate further efforts in analyzing and updating measurement techniques. Moreover, reliable data are needed on the spatial and temporal variability of the atmospheric and cloud electrical parameters to verify and calibrate numerical models of cloud electrification.

The techniques available for such measurements have progressed far during all the years the aircraft laboratories have been employed for these tasks. Placing field mills at cross points of the aircraft electric neutrals has become generally accepted. Adequate placement of such mills provided for favourable conditions of their operation and excluded the effects caused by cloud and precipitation particles, hitting the mills, by the charging dielectrics, and by space charges from the corona points [1,2,3].

Significant progress in estimating the form factors at field mill mounting positions [2,3] and explicit calibration of these sensors directly on board the aircraft [8] should be noted. Redundant sensors in the measurement system (in excess of four) were demonstrated to contribute to measurement accuracy [3].

The present author believes that a simple general principle may serve as a basis for a uniform approach to atmospheric measurements of the ambient electric field. Starting such measurements one has:

a) to identify all the possible sources of the electric fields affecting each sensor and try to eliminate them;

b) to identify and account for all the factors which might cause changes in form factors at the sensors' mounting positions;

The known factors from among their multitude are listed in Table 1. The "plus" sign in the table stands for indicate that such a factor should be accounted for, while the "minus" sign has an opposite meaning.

The factors listed under positions 1,2, and 5 of Table 1 are exhaustively treated in [2,3]. The systematic error source (position 4) is to be identified and eliminated in each given case, e.g., by coating the dielectric surfaces with conducting paints or by transferring the sensor to another position prior to measurements.

Consider in more detail the effects of other factors and the possibilities of accounting for them.

Table I

Factors to be accounted for during atmospheric measurements of the ambient electric field and the aircraft electric charge at various flight regimes

No Factor	Flight condition			
	Outside a cloud		Inside a cloud	
	E	Q	E	Q
1. Ambient electric field	-	+	-	+
2. Aircraft charge	+	-	+	-
3. Space charge at the aircraft surface	-	-	+	+
4. Charging of fairings, domes, and other dielectric surfaces	+	+	+	+
5. Measurement errors for form factors	+	+	+	+
6. Aircraft electric capacitance and its variations	-	+	+	+
7. Position of aircraft electric neutrals and their evolution	+	+	+	+
8. Inhomogeneities in the ambient electric field	+	+	+	+

1. SPACE ELECTRIC CHARGE AT THE AIRCRAFT SURFACE

According to [4] there exist two causes of space charge generation at the aircraft surface, differing in their nature. First, the electric charges are redistributed at the aircraft surface affected by the aircraft self-charge and the ambient electric field. Such a redistribution results in a space charge layer appearing at the aircraft surface, its ionic spectrum differing from that in free atmosphere. The electric field in the space charge layer affects the results of atmospheric field measurements, as well as measurements of the aircraft charge itself.

I.M.Imyanitov estimated this additional field strength produced by redistribution of air ions at the surface of a charged aircraft. He demonstrated that at ionic mobility of $K=2.10^{-4}cm^2/V{\cdot}s$ and a flight speed of $v=$ 50 m/s the additional field strength produced by a space charge layer would be about three orders of magnitude less than that of the principal field. Apparently, the higher is the aircraft flight speed, the less will be the additional charge density, so that conversely, the additional field will also be less. Such reasoning should apparently hold for flight speeds up to the shock ionization threshold for air molecules.

The effect of corona points and of sparking dielectrics (e.g., fairing and domes, cockpit window glass, etc.) which also alter the ionic spectrum at the aircraft surface is neglected here because it may be neutralized by the means mentioned in the Introduction.

The second cause for the space charge layer to appear, beside the airframe self-charging, is that particles colliding with an aircraft flying through clouds and precipitation, also charges [4].

Generation of a space charge by cloud and precipitation particles colliding with an aircraft is directly related to the process of aircraft electrification. Consider a simplified example of the conducting sphere charging in a homogeneous stream of single mode non-charged droplets. Let the first droplet colliding with the sphere deposit a charge of $-q$ at its surface due to contact potential difference between the droplet and the sphere substances. Having thus lost a charge of $-q$, the droplet will itself have a charge of $+q$ after detaching from the sphere (before the contact the droplet was electrically neutral). The electric field between the sphere and the droplet detached from it will be determined by the charge $-q$ of the sphere and that of the droplet $(+q)$.

Each following droplet contacting with the sphere will also deposit a charge $-q$ at the sphere. With the total charge accumulated by the sphere growing the new droplets detaching from it will carry away with them a part m of charge Q of the sphere, which will be proportional to the surface charge density at the sphere and to the electric capacitance of the droplet detaching from it [5,6]. The droplets with a charge of $(+q - mQ)$, detaching from the sphere and flying over it after detachment all contribute to the space electric charge forming, which has to be accounted for in our description of the process.

When the charge transferred by the colliding droplet equals that carried away by the detaching droplet ($q = mQ$), the charge of the sphere reaches its equilibrium state, and the droplets further detaching from the sphere will remain uncharged.

If we prevent, in some way, the sphere from reaching its equilibrium charge (e.g., lotting a charge leak from the sphere via the isolation resistance) a space charge produced by a stream of droplets detaching from it and carrying with them the charge opposite in sign to that of Q, will be constantly present around the sphere.

Consequently, if the surface charge density at the droplet detachment point at the surface of that sphere σ_i is such that the charge transferred by the droplet is equal to that carried away, a stream of such particles will produce no volume electric charge around the sphere. If the surface charge density at that point σ_i exceeds the respective equilibrium charge density, σ_e, the detaching droplets will produce a space charge above the sphere of the same sign as that of the sphere itself. On the other hand, if the surface charge density, σ_i, at the detachment point is less than the equilibrium density, σ_e, the stream of such droplets will generate a space charge of a sign opposite to that of the sphere.

Since the charge distribution over the aircraft surface is highly inhomogeneous and is strongly intensified at wing tips, tail empannage, the airframe nose, one may safely assume that areas of $\sigma_i > \sigma_e$, $\sigma_i < \sigma_e$, and $\sigma_i = \sigma_e$ may be found at the aircraft frontal surface.

To study explicitly the aircraft electrification features current sensors were mounted at the wing attack edge [4]. Metal plates safely isolated from the airframe served for such sensors. Each wing attack edge housed two such plates. One of them (plate 1) was placed approximately 1 meter off the hull, and the other (plate 2) - further out, close to the wing tip. It was assumed that such a placing would result in $\sigma_2 > \sigma_e$, $\sigma_1 < \sigma_e$. Measurements conducted with an aircraft model had demonstrated that $\sigma_2 >> \sigma_1$. The plates' profiles followed exactly the wing contour. Therefore conditions for the slip-stream at the plated wing area and the neighbouring areas could be considered identical. The plates were of wing metal, so that on the account of similarity in the aerodynamic and surface properties of wing proper and the plate one could assume the conditions of charge separation and droplet fragmentation at both surfaces to be identical. We had to neglect the differences in plate currents due to peculiarities of a slip-stream around a sweeped wing (the sweep angle difference between the positions of two plates was about 5^{o}).

Analyzing the currents to plates measured in flight we found that :

1. The current to plate 1 (positioned close to the hull) is always of the same sign as the overall aircraft charge;
2. If currents at both plates were of the same sign, the current to plate 2 was less than that to plate 1;
3. If currents to plates were of different signs, the current modules at plate 2 could be larger than that to plate 1. In the latter case the current to plate 2 coincided in its sign with the currents through the plane point dischargers.

The latter results indicates a strong collector discharge of the plane at its wings' attack surface, at least in the zone of wing tips.

The measured currents I_{p1} and I_{p2} may be used to calculate the conductivity λ_c, due to the collector effect. Having the value λ_c

is important, since it shows whether the plane is charged via the process typical for well-isolated bodies, or the situation is the opposite, and the discharge through the aircraft point discharges (λ_d), competing with λ_c is constantly holding the overall charge **Q** of the aircraft to a level **Q** < Q_e. Here **Q** is an equilibrium value of Q_e, with point dischargers disconnected.

Fig.1 shows part of a plane wing with current sensors, and the elements are shown from the circuit of plane discharge to the atmosphere.

The current I_p, recorded by the instruments connected to each plate is $I_p = I_c - I_{cp}$, where I_c is the charging current through a plate, and I_{cp} is the collector current from that plate.

Since the conditions for charge separation on each plate are the same, the difference between I_{p1} and I_{p2} will be produced by differences in the respective collector effects only, resulting from significant differences in the surface charge densities σ_1 and σ_2 at both plates.

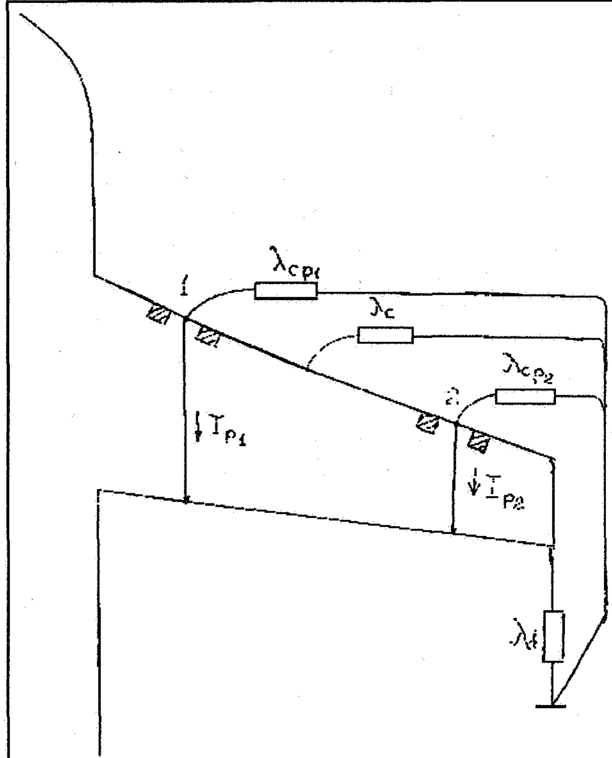


Fig.1. The equivalent electric circuit for currents to sensors measurements and the wing attack edges.

It follows from the electric scheme in Fig. 1:

$$I_{p1} = V_a(\lambda_d + \lambda_c + \lambda_{cp2})$$
$$I_{p2} = V_a(\lambda_d + \lambda_c + \lambda_{cp1}) \qquad (1)$$

Here V_a is the aircraft potential; $\lambda_{cp1}, \lambda_{cp2}$ are the discharging aircraft conductances due to the collector effect at plates 1 and 2, respectively.

It follows from (1) that

$$\lambda_{cp1} - \lambda_{cp2} = \frac{I_{p1} - I_{p2}}{V_a} = \frac{\Delta I_p}{V_a} \qquad (2)$$

Here I_{p1}, I_{p2}, V_a are the respective values measured in flight.

Since plate 2 is positioned close to the wing tip, and $\sigma_2 \gg \sigma_1$, we approximately have: $\lambda_{cp2} \gg \lambda_{cp1}$

It may be assumed then that:

$$\lambda_c \cong \lambda_{cp2} \frac{d_a}{d_{p2}} \cdot \frac{L}{\ell_p} \qquad (3)$$

Here α_{p2} is the relative surface charge density at the wing around plate 2; α_a is the average relative surface charge density for all the droplet capturing surfaces; L/l_p is the total aircraft capturing zone to plate zone lengths' ratio.

We have calculated I_{p1}, I_{p2}, Q in liquid droplet clouds from the measured currents (flight level: 4.2 km; air speed: 650 km/hr) and found $\lambda_c = 10^{-9}$ Ohm^{-1} for these conditions. The value of λ_d for the same conditions is approximately $2\cdot10^{-9}$ Ohm^{-1}. It is experimentally found that λ_c is proportional to squared air speed [9], and λ_d is linear on that speed [10]. Besides, λ_c also depends on the cloud water content and the size of droplets colliding with the aircraft [6,7,12]. Studying electrification of a Tu-104 aircraft empirical expressions were found to relate the values of λ_d and λ_c with the medium and aircraft characteristics. These expressions may be used to estimate the change in λ_c/λ_d ratio in the aircraft discharge circuit, and to assess the regime of aircraft charging.

According to [7] $\lambda_c \cong D\cdot w\cdot v/r$, $\lambda_d \cong B\cdot v\cdot(P_0/P)^{0.4}$. Here w is the cloud water content, v is the air speed; r is the cloud droplet average radius. We have for the Tu-104 aircraft $D \cong 0.9\cdot10^{-15}$ $Cm\cdot m^2s^2kg^{-1}$, $B \cong 10^{-11}$ $Cm\cdot s\ m^{-1}$.

Computational results on λ_c/λ_d for two air speeds of 100 and 200 m/s are shown in Fig.2 for cloud droplet radii 10, 20, 30, and 100 μm, and the cloud water content raised to 2 g/m^3. It follows from these computations that $\lambda_c < \lambda_d$ for large droplet size clouds only. Fine droplet size clouds and clouds of high water content always give $\lambda_c > \lambda_d$. Higher air speeds resulting in more intense droplet fragmentation upon collision with the aircraft surface , increase the role of λ_c in aircraft discharging process, as compared with that of λ_d. That means that at higher air speeds the point at the wing edge where $\sigma_i = \sigma_e$ moves closer to the airframe. Inversely, that point will move to wing tip at low cloud water contents and in particles of large droplet size.

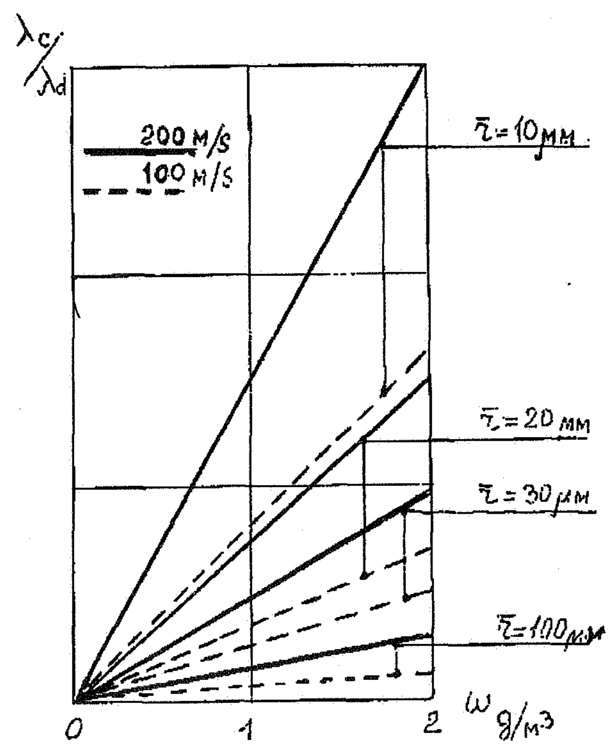


Fig.2. The effective electric conductances λ_c and the λ_d ratio for various flight conditions.

We may conclude that because of a change in cloud properties above and below the wing the density of the space charge formed by droplets fragmenting upon collision with the aircraft, will be minimum within the possible shifting range of the $\sigma_i = \sigma_e$ at wing end point. Below we shall estimate the limits of that range. To do that we also have to account for the conductivity of the aircraft engine exhaust gases, i.e. consider the value ($\lambda_c/(\lambda_d + \lambda_e)$).

If our reasoning is correct, the airframe would apparently be slipstreamed by an airflow with a high density of space charge. The nose part of the air frame being non-symmetrical in the vertical, these flows may considerably differ above and below the frame.

Prof. Imyanitov [4] estimated the additional field strength due to these changes. He demonstrated that it may be comparable or even exceed the ambient electric field and the field of the aircraft electric charge. Considering also the effect of the space electric charge, the airframe should not be considered the best place for mounting the measurement system sensors.

From that point of view a better place to fit much sensors would appear to be the wing edge, where $\sigma_i = \sigma_e$. (see Fig 3)

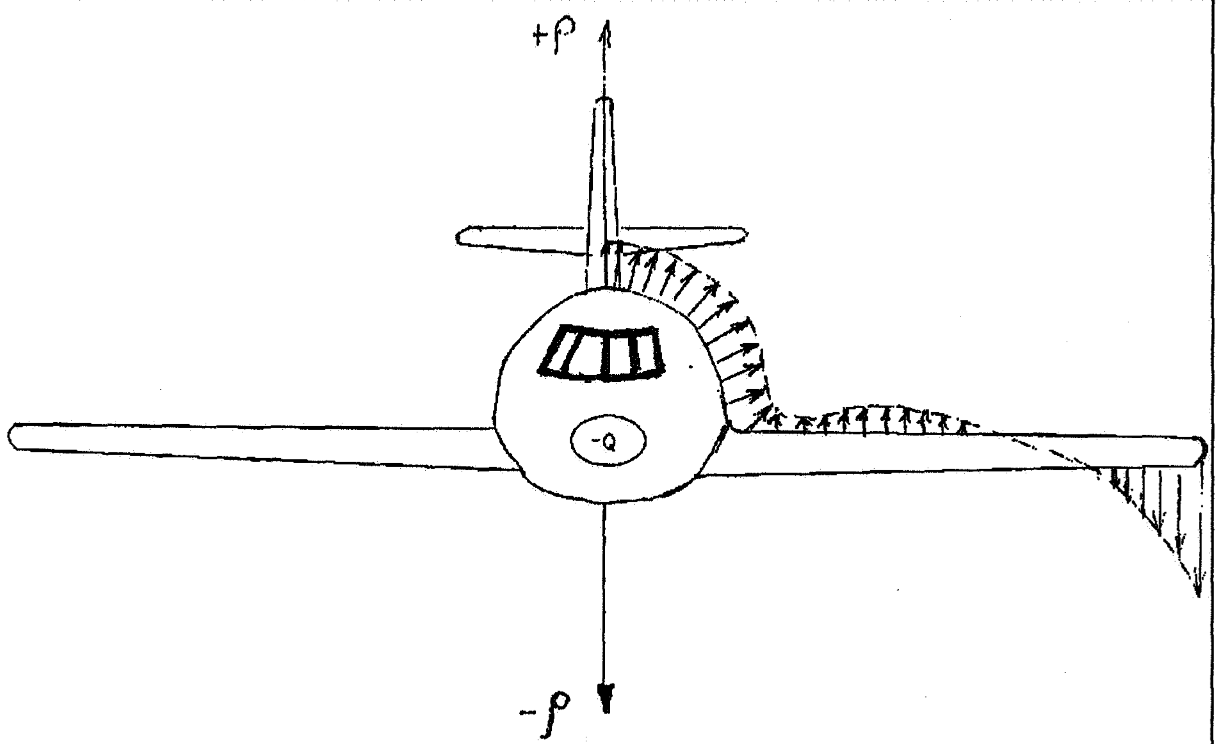


Fig.3. Quantitative distribution of space charge above the airframe and wings.

2. THE ELECTRIC CAPACITANCE OF THE AIRCRAFT AND THE POSITION OF ELECTRIC NEUTRALS

As an isolated conducting body the aircraft has a certain electric capacitance. This capacitance is usually assumed to be constant, since it is determined by the characteristic linear size of the airframe. The high-temperature rocket jet exhaust are known to increase the respective length of a rocket conductive body by almost a factor of two. However, significantly lower exhaust temperatures of the turboprop and jet engines precluded even suggesting a possibility of such an effect for aircraft.

Trinks and Haseborg [11] studied electric fields at the Earth surface after an aircraft passed above the observation site. They recorded the position of a hypothetical chargecenter of the aircraft using a little sensor had a small load resistance and indicated that center point as the signal passing its zero. Studies by these authors demonstrated that the charge center was biased to the artificial tail, and for some aircraft types even got behind the actual tail end. This experimental fact may only be explained by the effect of low-temperature gas jets, which appears to be capable of somewhat "elongating" the airframe. Another simple measurements may be applied to assess the role of the engines' exhaust jets. It is enough to compare the surface charge distribution over a model aircraft with its actual distribution over the frame in a longitudinal electric field. Two flight legs are needed for such an experiment; one leading to, and another - from a thundercloud. Comparing the relative distribution of the induced charges along the airframe with that along the model should demonstrate whether a displacement takes place of the electric neutrals. The positive result of such an experiment would testify to airframe "elongation", hence - to an increase in the aircraft capacitance.

Modelling the exhaust jets by as conducting cylinders attached to the aircraft model, the same relative displacement of the electric neutrals may be obtained as that actually observed. The capacitance of such a system would serve a better presentation of the actual aircraft capacitance in flight.

3. INHOMOGENEITY OF THE AMBIENT ELECTRIC FIELD

Form factors at sensor locations are estimated in a homogeneous electric field. Using such factors to calculate the components of the ambient field vector and the aircraft charge in case that field is significantly inhomogeneous, would lead to noticeable errors in **E** and **Q**. Apparently, the longer is the base, at which the sensors are placed to compute **E** and **Q** from their signals, the more homogeneous should the ambient field be, if only we went to stay within the prescribed error limits for both the field and the charge. However, it is advisable to position the sensor along small bases to achieve high spatial resolution in **E**. We again return to the already discussed option: of placing sensors at aircraft wings: the wing thickness is an order of magnitude less than the diameter of the hull. Placing two sensors along a wing chord would result in obtaining information on the longitudinal field component from a small base. The field transverse component may be measured by any pair of sensors in a differential circuit. Such a system features the needed redundancy, it may be positioned in the zone of minimal effect from space charges (see Fig. 4), and moreover, placing these sensors at wing may help estimate the form factors directly in flight.

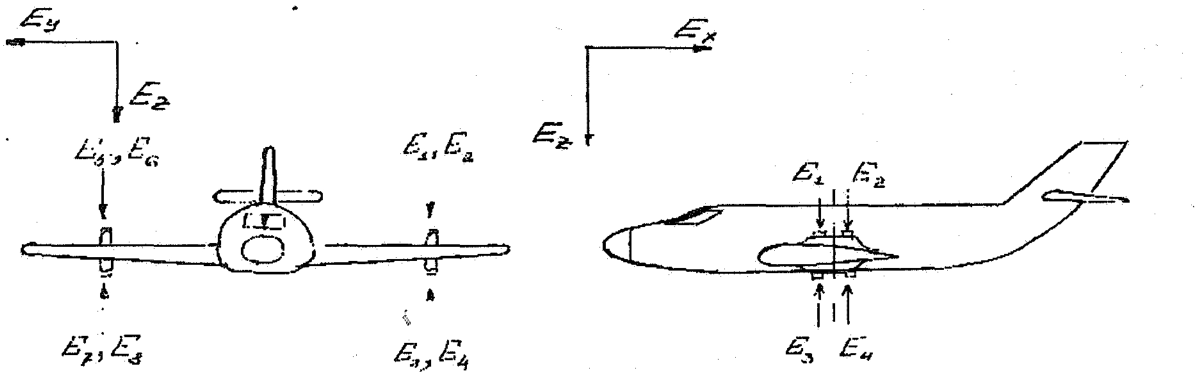
4. FORM FACTORS FOR THE AIRCRAFT CHARGE

An approach is well known to estimating, model and flight testing the form factors, which relate the ambient electric field with the local one at the sensor locations [2,3,8,13].

Of certain interest are ways and means for estimating such factors, which relate the aircraft charge and the field at sensor locations. One of such means may be measuring the field produced by a charged aircraft flying by the surface field sensors at a low altitude [11]. The aircraft charge may be calculated if the flight level is accurately known. The second approach to that task is artificial charging of an aircraft from an on board source. Controlling the charging current and making sure that the charge only leaks via air and the exhaust jets conductances (these values may be measured and accounted for) we may compute the running charge value:

$$Q = \int_0^{t_1} i \Delta t$$

where **i** is the measured charging current. Then one may compare the running value of **Q** with local fields at sensor positions to retrieve the respective form factors.



$$\begin{aligned} a_1 &= a_5 & a_3 &= a_7 \\ b_1 &= b_5 & b_3 &= b_7 \\ c_1 &= c_5 & c_3 &= c_7 \\ d_1 &= d_5 & d_3 &= d_7 \\ a_2 &= a_6 & a_4 &= a_8 \\ b_2 &= b_6 & b_4 &= b_8 \\ c_2 &= c_6 & c_4 &= c_8 \\ d_2 &= d_6 & d_4 &= d_8 \end{aligned}$$

$$\begin{aligned} E_1 &= a_1 E_z + b_1 E_x + c_1 E_y + d_1 Q \\ E_2 &= a_2 E_z - b_2 E_x + c_2 E_y + d_2 Q \\ E_3 &= -a_3 E_z + b_3 E_x + c_3 E_y + d_3 Q \\ E_4 &= -a_4 E_z - b_4 E_x + c_4 E_y + d_4 Q \\ E_5 &= a_5 E_z + b_5 E_x - c_5 E_y + d_5 Q \\ E_6 &= a_6 E_z - b_6 E_x - c_6 E_y + d_5 Q \\ E_7 &= -a_7 E_z + b_7 E_x - c_7 E_y + d_7 Q \\ E_8 &= -a_8 E_z - b_8 E_x - c_8 E_y + d_8 Q \end{aligned}$$

Fig.4. Sensors' placements at aircraft wings and the respective equations.

CONCLUSION

Increasing the measurement accuracy for both the electric field and charge of a flying vehicle is seen as a solvable problem. The present paper put forward the problem certain considerations on that problem for critical attention of the scientific community. They touch on the need to account for additional space charges resulting from the appearance of an aircraft in airspace, on the techniques for estimating the actual aircraft capacitance seen as an isolated body; on the possible changes in form factors caused by a displacement of the aircraft electric neutrals, because of the influence from the attached conducting engine exhaust jets.

It is believed that preparing an aircraft laboratory for in-flight measurements in the free atmosphere should include the following steps:

1. Estimating external factors which interfere with the measurements - the presence of charging fairings, of the corona points, and the space charge distribution at the aircraft surface;

2. Estimating form factors at an aircraft model or via numerical simulation;

3. Updating form factors (for both field and charge) at the aircraft;

4. Adjusting the electric capacitance and form factors in the computational matrix;

5. Estimating the admissible limits of spatial and temporal variability of the signals measured to retrieve the ambient electric field in the aircraft environment.

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