ERRORS DURING AIRCRAFT MEASUREMENTS OF THE ELECTRIC FIELD AND WAYS TO REDUCE THEM

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ABSTRACT. Analysis is suggested of basic errors appearing during aircraft measurements of the vector electric field in the atmosphere (E) and of the aircraft charge (Q). A technique is described to reduce errors in measuring the value of Q during flights outside clouds and other aerosol formations. Such errors are produced by inaccurate retrieval of form factors for E and Q. The form factors account for the fact that an aircraft is an electrically charged body of complex shape. Various approaches are pursued to compensate for the aircraft self-charge. Measurements are specifically taken in prescribed flight regimes when a priori information becomes available on E, on its separate components, or on the relation between these components and the value and sign of Q. Electric field measurements in clouds and aerosol formations are aggravated with additional difficulties since current generators acting upon the aircraft are highly powerful. Hence the principal assumptions on the homogeneity of the external field and the equipotentiality of the aircraft surface are violated.. In these conditions some blunders are possible. Certain approaches are suggested to reduce such errors in these conditions.

1. INTRODUCTION

Starting from the 1950s, aircraft measurement techniques for E have been initiated and developed in the USSR under I. M. Imyanitov and were oriented on using field mills. Form factors for specific locations of sensors on the aircraft hull (K) were found through placing aircraft models in a flat capacitor. As for the piston-engine aircraft, their self-charge remained small and did not affect the measurement accuracy in any significant way. The accuracy of aircraft measurements of E was of the same order of magnitude as that of the field mills themselves and amounted to a sensitivity several volts per meter, so that soundings of E from the Earth's surface up to the height of 5-6 km were possible [Imyanitov, 1957].

In 1979 the new Soviet meteorological airborne laboratories (ACL) based on the new generation of aircraft (AN-12 and IL-18) were introduced and outfitted. The first experience of taking measurements from aboard these aircraft revealed certain problems, the most important among them being the strong charging of aircraft in the clear atmosphere (E>10000 V/m) and the noticeable differences between the actual form factors, K, and the model ones. These circumstances forced us to fall back to analyzing the initial techniques of aircraft measurements of E and Q and to look for ways and means to update them [Belov et al., 1990].

It appeared at some later stage that these efforts were actually within the mainstream of foreign studies aimed at solving similar tasks [Mazur et al., 1986; Hewitt et al., 1989; Anderson and Bailey, 1986; Easterbrook et al., 1988; Jones, 1991; Kositsky and Nanevicz, 1991; Giori et al., 1992]

It's necessary to underline that errors in measurements of E may be the origin of incorrect cloud electrification theories. For example, electrification of warm clouds, the existence of small areas with high meanings of E and so on. Especially it applies to the measurements in the clouds.

2. AIRCRAFT MEASUREMENTS OF E IN A CLEAR ATMOSPHERE

Methodologically, aircraft measurements of E are a complex problem even during aircraft flights outside clouds and other aerosol formations. Difficulties are produced by the strong perturbing effect of ACL self-charge and the fact that the ACL itself is a conducting body of complex shape which locally perturbs the measured field. The electric field measured by the i-th sensor E may be presented as

$$Ei^{S} = fi\ (k_{ix}, k_{iy}, k_{iz}, k_{iq}, Ex, Ey, Ez, Eq) \qquad (1)$$

Or in its matrix form

$$E^{S} = K\ E^{EQ} \qquad (2)$$

where Ex, Ey, Ez are the orthogonal components of the computed vector E in the system of coordinates related to the aircraft, and kix, kiy, kiz, kiq are the form factors for the i - th sensor.

Solving (2) with respect to E^{EQ} (assuming i=1, 2, 3, 4) we obtain

$$E^{EQ} = K^{-1}\ E^{S} \qquad (3)$$

Or, more generally for i=1 to n and j = x,y,z,q

$$Ej^{EQ} = Fj\ (k_{1j},\ k_{nj},\ E_1^{S},\ldots,E_n^{S}) \qquad (4)$$

The absolute measurement error for E is equal to

$$(dEj^{EQ}) = (dFj/dK_{1j})^2\ (dK_{1j})^2 + \ldots + (dFj/dKnj)^2\ (dKnj)^2 + (dFj/dE_{1s})^2\ (dE_{1s})^2 + \ldots + (dFj/dEns)^2\ (dEns)^2 \quad (5)$$

Analyzing expression (5) one can identify the principal approaches to the task of reducing dE^{EQ}, which are **(1)** reducing the number of terms in (5) by placing the sensors at electric neutrals or at their cross-points, so that respective terms of the form dFj/dKij and dFj/dEis be zeroed; **(2)** placing the sensors at points of the lowest nonzero values of dFj/dKij and dFj/dEi; **(3)** reducing the errors in form factors, dKij themselves; and **(4)** reducing the measurement errors for every individual sensor, dEis (we imply the absolute errors hereafter).

2.1. Reducing dE^{EQ} Via Optimal Placing of Sensors

As shown by our experience and studies by Mazur [1986], the first two approaches to reducing the overall error, indicated above (tasks 1 and 2) are quite efficient. There exist, however, numerous design, technical, methodological, and other limitations in placing sensors at the hull, which prevent implementing these in full. Such considerations are particularly important for modern ACL, outfitted, as they are, with numerous sensors and antennas. At the same time such approaches are often taken by both the present authors and the other researchers to make a quasi-optimal choice of sensor placement at the hull, using at least the approximate values of Kij, dKij, and dEis. Using recommendation of task 2. We can approximately evaluate the changing character and magnitude of dFj/dk_{ij} and dFj/dEis either from physical considerations or on the basis of a numerical simulation of the aircraft or certain parts of its fuselage, or from laboratory experiments with a scale model in a flat condensator. I.M. Imyanitov and his colleagues carry out detailed investigations of the scale models of aircraft IL-18 (Illiyushin's construction) and TU-104 (Tupolev's construction). The technique these investigations used was similar to the one of Kositsky and Nanevicz [1991].

At present we act mostly in accordance with general assumptions that dFj/dk_{ij} and dFj/dEis are being high near tips and small curvatures of the fuselage surface, due to reasons presented below in sections 2.2, 2.3, 2.4, and 3. Hence we tend to place sensors possibly closer to the region of centriplane, for example, on top for AN-12 and at the bottom for IL-18. Main Geophysical observatory's aircraft IL-18 had two sensors situated on top of the fuselage on 15 and 51 frames, instead of the of the tail sensors traditionally used, to determine a longitudinal component Ex . In our preliminary result we had a more complicated calculation procedure, but a higher calculation accuracy was obtained for Ex measurements. Note that impressive reserves for increasing the accuracy and reliability of aircraft measurements of E^{EQ} lie with using excessive sensors [Vinnichenko et al., 1986; Hewitt et al. 1989]. The value of E^{EQ} is then found from the condition of minimizing

$k = S\ (Eis - fi\ (K, E^{EQ}))^2$ (6) instead of using the exact solution of (3).

2.2. Reducing dE^{EQ} Via Lowering the Errors Due to Self-Charging of the Aircraft

As demonstrated by actual studies, the tension of field produced by the hull self-charge of an ACL of the IL-18 type, EQ, reaches 10000 V/m even in cloudless atmosphere. At the same time, various problems of the physics of the atmosphere call for measuring the values of E of an order of several volts per meter. Naturally, such measurements are totally impossible without using some special techniques to compensate the field produced by the aircraft self-charge. To reduce the errors due to self-charge of the aircraft, we addressed the following techniques**:** **(1)** compensating the signal due to ACL Q at amplifier input; **(2)** compensating the signal due to ACL Q at amplifier output ; **(3)** compensating the field of ACL Q at sensor positions; **(4)** compensating the aircraft overall charge. In cases (1) and (2) a signal is formed by a special device which is proportional to the value of ACL Q, which is transmitted via a solving device to both the input and the output of the amplifier unit of every sensor with its respective sign. In case (3) the signal is transmitted to special calibrating plates of sensors. Thus the field produced by the ACL hull charge, EQ , is practically compensated, and only the signal from the external field EE is fed to the amplifier input. In case (4) the ACL charge is directly compensated over the whole hull by corona currents from special discharging tips (SDT). Errors in cases (1), (2), and (3), are basically of random character, but strict limitations are imposed upon the accuracy to which the form factors are known. In case (4) these restrictions are lifted, since these automatically met, however systematic errors become possible, which are associated with the effect of ion jets escaping those discharging tips. In general, by decreasing E^{Q}, one may significantly lower dE_i^s and dE^{EQ}.

2.3. Reducing dE^{EQ} Via Increasing Retrieval Accuracy for the Form Factors Kij

Studies from the last few years have demonstrated a large reserve for decreasing dE^{EQ} to lie with higher retrieval accuracy of the form factor matrix K. The available experimental and theoretical techniques of finding K (these are model measurements in a flat capacitor and theoretical calculations) are apparently incapable of providing the needed accuracy even if modern approaches are pursued [Hewitt et al., 1989; Easterbrook et al., 1988; Kositsky and Nanevicz, 1991] because of significant differences between the models and the actual ACLs in flight. Such differences result from the presence of highly ionized jets from engines and of other sources actually altering the shape of ACL electric body and capacity and from the complexity of the task of simulating various antennas and fairings, including those carrying the E sensors themselves.

We believe this is also confirmed by results obtained by Kositsky and Nanevicz [1991], Giori et al.,[1992]. Particularly for the aircraft Lear jet 36A a comparison between form factors from scale-model measurements and those from in-flight data during pitch maneuvers shows a 40% difference [see Table 3, Kositsky and Nanevicz, 1991]. The difference may be due to the presence of charging jets from the Lear jet 36A engines, because the point where the form factors were measured lay close to the engines [Giori et al., 1992]. For several form factors we got errors to exceed 100%. This may be stipulated by the lack of accuracy of scale-model measurements, the placement of field mills inside the fairings on the outside of the fuselage and the poor technology in making engines result in a higher charge of their jets. Taking all this into account, we developed several techniques for either retrieving or updating the K matrix for any given ACL or even specific flight mode. These are based on applying equations (2) and (3) to the task. By prescribing certain flight modes which provide a priori information on the E^{EQ} vector (the values of and relations between its components), we can solve (2) or (3) with respect to K.

Such flight modes may be as follows: **1.**Flights are in clear cloudless atmosphere at high altitudes (H > 6 km) while simultaneously varying the ACL overall charge. Such variations of charge may be achieved by either altering the engine regime or introducing active compensators. In this case, Ex=Ey=Ez=0, Q=variable (VAR). **2**.Flights are in clear atmosphere at low heights (H<100m) in the Earth's homogeneous field while simultaneously varying the ACL charge. In this case, Ex=Ey=0, Ez=const=C, Q=VAR. **3**.Flights are in clear atmosphere in the Earth's homogeneous field at constant Q and constant tilt (roll angle) a. In this case, Ex=0, Ey=Csinα, Ez=Ccosα, Q=const . **4**.Flights are in clear atmosphere in the Earth's homogenous field at constant Q and constant pitch q . In this case, Ex=Csinθ, Ey=0, Ez=Ccosθ, Q=const**.** **5**.Flights are in clear atmosphere in the proximity of clouds during lightning discharges. In this case, dEx/dt/=0, dEy/dt/=0, dEz/dt/=0, dQ/dt=0. **6**.Flights are in clear atmosphere in the proximity of electrified clouds. In this case, Q=const, E^E=VAR. **7**.Flights are of two ACLs, one of which plays the role of the source of homogeneous electric field for the other ACL whose form factors are to be found. Let r be the radius vector of the "source aircraft" (Q') in the coordinate system of the "measuring aircraft." Instead of the "source aircraft" an electrified cloud or some other charged target in the atmosphere or at the surface may also be used, as long as its electric structure may be presented in the form of some charge or dipole. In this case, Ex=fx(Q', r), Ey=fy(Q', r), Ez=fz(Q', r), Q=const**.** **8**.Flights are in clear atmosphere in the proximity of an electrified cloud or of a "source ACL," further to apply parameterization programs developed in MGO. In this case the source is presented as a system of point sources q_i with coordinates r_i which form the field e_{ij} at point "j" of the flight track. The designed function is minimized with respect to q_i and K simultaneously. In this case $(F (q_i r_{ij}) - KE^S)^2$ == min **9.**Flights are of ACL bearing charge Q' at low heights in clear atmosphere over a sensor placed at ground and measuring the field of that ACL charge, E'. Let r' be the radius vector of ACL with respect to that sensor. In this case, Q'=const, E'=G(Q',r'). To lower the errors associated with the inaccuracy of finding r', one may try to solve the problem S(E'j-Ejr)==min, where E' are the measured values of E and Er are the calculated values. When operating in modes which assume a constant charge of the ACL (see methods 3, 4, 6, 7 and 8), one should pay close attention to the possible changes of Q due to ACL polarizing within the external field so that the corona discharge currents from ACL discharge tips may change, including special discharging tips. This circumstance limits the possible value of the external field, in the sense that changes of that field should not result in changes of corona emanating from ACL discharge tips.

2.4. Results and Recommendations

The means for reducing measurement errors for E described above were tested on all the aircraft from which the MGO experts conducted electric field measurements (IL-14, TU-104, IL-18 "Cyclone," AN-12 "Cyclone," IL-18 MGO, YaK-40, AN-24). These methods were analyzed in greatest detail for the AN-12 aircraft, since cloud electrization studies were conducted recently. The AN-12 aircraft was equipped with four field mills, placed following the traditional scheme (top, bottom, side, tail), close to cross-points for electric neutrals. The aircraft was also equipped with two active compensators whose tips were positioned in the side illuminators at 5 m past the wing, close to cross-points of the ACL electric neutrals. All the above mentioned means for retrieving and updating the K matrix (methods 1 through 9) were tested for that ACL. The initially applied technique of constant tilt and constant pitch flights in the Earth's field (methods 2, 3 and 4), also described by Anderson and Bailey [1986], appeared to be poorly effective for this type of aircraft. When flying at low altitudes, as demanded by that technique, the power of active compensators appeared to be insufficient to counteract the aircraft-charging currents of the engines. Experimenters were forced to practically switch off the engines, such that the flight time for such a mode was naturally limited to a few dozen seconds. Recalling that the aircraft capacity is high, while the atmosphere conductivity at low altitudes below 100 m is poor, one can easily imagine the kind of difficulties encountered when trying to sustain a stationary regime of compensation for ACL charge in such conditions [Lishter et al., 1988]. Despite persistent efforts by the crew, experimenters failed to achieve the necessary retrieval accuracy for form factors using that technique. Application of the approaches described under methods 1, 5, 6, 7, 8 and 9 have enjoyed much more success. The result of all these methods is that the K matrix underwent considerable changes (Tables 1 and 2).

	The initial K matrix				The final K matrix			
	Ex	Ey	Ez	Eq	Ex	Ey	Ez	Eq
top	0	0	1.67	0.55	0.07	0	3.04	0.32
bottom	0	0	3.51	0.74	0.05	0	5.53	0.64
side	0	0.52	0	0.43	0.06	1.74	0.14	0.32
tail	1.03	0	0	1.00	4.11	0	1.13	0.84

One sees that no sensor is placed exactly at a cross-point of electric neutrals, although the top, bottom, and side sensors are positioned quite close to those points. Note also that the form of K is not so much determined by the type of aircraft itself as by the specifics of the mounting of the sensors (such as shape and dimensions of the fairings, the presence or absence of other fairings, antennas, discharge tips and other elements close to that mounting). To give an example, the ratio of the charge form factors for top and bottom sensors, $k_1=k_t^q/k_b^q$, reaches $k_1=1.8$ for the IL-18 "Cyclone," while $k_1=0.8$ for the IL-18 MGO. Hence disregarding specific features of sensor mounting and placement may result in extreme blunders, up to the very sign of the effect, even for flight conditions outside clouds.

Another example of a successful application of the developed techniques is measuring the vertical trend of the electric field from aboard the IL-18 MGO aircraft (six field mills) during the 1989 Soviet-American "ozone" experiment in the Arctic region. Various techniques were applied to reduce the errors produced by the aircraft self-charge (see methods 2, 3 and 4), so that fields of the order of several volts per meter could be measured

3. MEASUREMENTS IN CLOUDS AND PRECIPITATION ZONES

As follows from our own experience and studies by other researchers, e.g., Jones [1991], charging of aircraft resulting from its collision with cloud particles heavily aggravates difficulties of the measurement process. Dielectric parts of the ACL outer surfaces break up the assumed equipotentiality of the hull. Data are available, indicating that the scale of inhomogeneous in E inside clouds is comparable to the base over which field mill sensors are placed [Imyanitov, 1976]. Differences in the character of cloud particulate matter slip streaming along the hull, and the fact that matter can be charged due to the processes inside the cloud and to the collisions with aircraft, result in "artificial" inhomogeneous of the special charge and of E around the ACL. ACL-charging currents reach several milliamperes, so that active compensators become ineffective. Therefore only recommendations of an extremely general character may be suggested for such conditions so that one can follow them while evading obvious blunders in retrieving the value and the direction of E. Among them one may mention the following: painting the dielectric fairings with microwave transparent conductive paint or placing the sensors at positions sufficiently removed from such fairings; reducing the base of sensor placement; mounting sensors in zones of minimal effect from "artificial" space charge (e. g., at the wings), or accounting for the symmetry of that charge. We believe extensive theoretical and experimental studies under natural conditions and simulation experiments with models in wind tunnels are necessary for reliable and accurate measurements of E in clouds.

The conclusion of the article may be formulated as the following: it's very high the possibility of blunders without the participation of the experts in aircraft measurements and without employment of special methodic.

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