Measurements of global current density and electric field in urban environment

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Abstract. Results of continuous and simultaneous measurements of global current density (flowing between ionosphere and the earth) and electric field intensity (in the vicinity of the earth surface) are presented. The results were obtained in a measuring system placed 20 m above ground level. Using the continuity equation, the conductive and displacement components of current density (as well as conductivity of the atmosphere) were determined. It was found that the displacement part of the total current is much smaller in comparison to the conduction one. Analysis of measurement showed a high coincidence of the electric field derivative with the time course of the global current. Temporal courses of conductivity indicate the presence of space charge and suggests the continuity equation is supplemented with a space charge component. The calculated average value of the short-period (10 min long) current density was found to be on the level of 2-3 pA m⁻² (average conductivity of the order of 15-20 fS m⁻¹). At the same time period the average value of field intensity was on the level of 150-300 V m⁻¹.

1. Introduction
In fair weather conditions, through the atmosphere flows so called global electric current, which density is estimated to be on a level of 1-2 pA m⁻² [1, 2]. The global current flows between ionosphere and the ground due to charge carriers produced during atmospheric electrical discharges (in thunderstorm regions), as well as the effect of their generation by cosmic rays and others sources of high-energy radiation and by radon. In the first approximation ionosphere may be considered as a specific, weak-conducting "electrode" with potential on the level of (+) 250-300 kV [3]. Values of electric field created in the ionosphere-earth space as well as global current density, measured locally, are (or can be) "modulated" by the temporary presence of clouds in the space. Additional component is the displacement current, flowing due to natural fluctuations of the electrical field intensity in the ionosphere – earth space as well as in the nearest vicinity of the measuring electrode employed for charge carriers collecting.

2. Global current density
The measurement of global current density \( j_T \) is carried out by measurements of total current \( I_T \) flowing between an isolated (from a ground) collecting electrode and the earth. The electrode is...
exposed to natural (global) electric field $E$ and charge carriers stream moving in the electric field. Basic measurement system is shown in figure 1.

Figure 1. Basic set-up of current density measurement system.

The average current density $j$ is associated with the measured total current value $I_T$ by a relationship:

$$I_T = j \cdot s$$

where $s$ is a surface of the measuring electrode.

The current density $j$ measured in the plane of the earth is determined by two components: drift (conductivity) current, resulting from the motion of electrons and atmospheric ions in electrical field $E(t)$ and a displacement current resulting from $E(t)$ changes with time. For the total current density $j$ one can write:

$$j = \sigma_T \cdot E(t) + \varepsilon_0 \varepsilon \frac{dE(t)}{dt} = \frac{I_T}{s}$$

where $\sigma_T$ – conductivity of the atmosphere (air) surrounding the measured electrode, $\varepsilon$ – relative permittivity of the atmosphere; $\varepsilon_0 = 8.85 \times 10^{-12} \text{ Fm}^{-1}$ - permittivity of vacuum. Assuming for the air $\varepsilon=1$, the expression (2) can be transformed into the form allowing determine the conductivity $\sigma_T$:

$$\sigma_T = \left[ \frac{I_T}{s} - \varepsilon_0 \frac{dE(t)}{dt} \right] \cdot \frac{1}{E(t)}$$

3. Measurements system

The prototype E-U transducer FM-09 field-mill type [4], was used for the continuous measurements of the electric field $E(t)$ intensity. The transducer offers sensitivity on the level of 3-4 V m$^{-1}$ and provides linearity of the conversion characteristic for the field intensity measured in a range of $0 \pm 10$ kV m$^{-1}$. With conversion characteristic slope equal to $1.0 \pm 0.05 \times 10^{-3}$ $\text{m} / (1\text{[V]}/1\text{[kV m}^{-1}])$. The transducer (FM) was mounted at the edge of a building, at the height of about 20 m above the ground. Details of the whole installation (geometry) are given in figure 2.

The measuring electrode (ME), collecting charge creating the total current $I_T(t)$ was mounted at a distance of 0.85±0.01 and parallel to the conductive surface of the terrace – floor. Details of construction of the collecting electrode and its installation are shown in figure 3. The electrode is made in the form of an aluminum plate with dimensions 1.00 x 2.00 m and 3.0 mm thick.
Figure 2. Distribution of the whole devices applied for simultaneous measurements of the global current and field strength. Symbols: FM - field meter, ME - measuring electrode, A - current meter, ADC - analog-digital converter and multiplexer, PC - a computer. MC - measuring chamber, SC – screen, T – table.

The plate is supported in six places by polymeric insulators (I) with a diameter of 50 mm and a height of 80 mm. The insulators are mounted on a grounded steel bars. Surfaces of insulators submitted to the direct contact with the measuring electrode were covered with a graphite layer, in order to avoid the "microphone" effect due to a charge deposited on insulators and natural vibrations of the whole electrode. Steel bars were earthed and placed on the screen (SC) created by a second aluminum plate. The screen dimensions were identical to the dimensions of the measuring electrode. The whole system is mounted on the surface of week-conducting tables (T), to ensure the lack of its own electric field. The analog current-meter (A) (Pico-ammeter, type PA-100) placed in the earthed

Figure 3. Sketch of the electrode system for measuring the global current – side view. Symbols: ME – measuring electrode, T – table (conducting), SC – screen, A – current meter tip I - support insulators, TS – temporary shielding, CS – conducting shielding support.

Measuring chamber (MC) was employed to measure the total current $I_d(t)$. Registration of the field strength $E_{id}(t)$ and the current $I_d(t)$ was performed using a PC and Agilent 34970 (used as an A/D converter and multiplexer).

Before current measurements the system was examined for the influence of parasitic signals. Current components due to electrochemical and Volta potential, piezo- or pseudo-piezoelectric effects
(related to the charge that may be accumulated during assembly and manipulation of the measuring electrode on support insulators) were considered. In order to verify the mentioned disturbances an additional screen (TS) was temporarily mounted on conductive supports (CS) at a distance of $0.20 \pm 0.01$ m above the surface of the measuring electrode (ME). This procedure allowed to determine the real value of the parasitic part of the total current $I_T(t)$.

Due to a field distribution in space of the whole measuring system (including the field-meter (FM) and the electrode (ME) for measuring the global current as well as due to a field distribution on the surface of the electrode (ME), the average value of the field strength $E$ at the surface of electrode (ME) was determined from relationship:

$$ E = E_M K_E K_D $$

where: $E_M$ - field strength measured by the transducer-meter placed on the edge of the building (see figure 2), $K_E$ - constant, determined from the formula:

$$ K_E = \frac{E_E}{E_M} $$

$K_D$ – constant, determined from the formula:

$$ K_D = \frac{E}{E_E} $$

where: $E_E$ - the value of field strength measured in the center of the measuring electrode (ME) and in its plane. Value of $K_E$ constant was determined from equation (6) using results of simultaneous measurements of fields $E_M$ (measured as described above) and $E_E$ measured in the middle of the measuring electrode (ME). The JCI-141F field-meter, with measuring aperture co-planar with the surface of the measuring electrode (ME) was applied for the temporal measurement of $E_E$ value. The value of $K_D$ (the ratio of the average field strength over the whole surface of the electrode $E$ to the intensity $E_E$ in its central part) was determined from relation (7) using simulation of the field distribution along a flat electrode, assuming the geometry as shown in figure 3. Received values for $K_E = 0.075 \pm 0.001$ (field strength at the edge of the building is much higher than at the plane electrode) and $K_D = 1.4 \pm 0.1$ (mean value of the field strength is higher than the values measured in the central part of the electrode) allow to determine the real average value of the field $E(t)$. The global current density was calculated from the relation (2) assuming area of the surface of measuring electrode (ME) $s = 2.00$ m$^2$.

4. Measurement results and discussion

An example of measurements results of the average value of the field strength $E(t)$ in the plane of measuring electrode (ME), obtained for the case of "fair weather", is shown in figure 4. Before measurements of global current density, the influence of parasitic signals was examined. Current value measurements, in situation of shielding the measuring electrode (ME) with applied temporary screen (TS) showed, that the average current density $j_{Ts}(t)$ after shielding does not exceed 10% of the value after removal of the screen (TS). Measurements confirmed that the electrochemical and piezoelectric components of the total current were negligible.

Comparison of measurement results of the global current density $j_I(t)$ and field strength, given in the form of derivative $dE(t)/dt$, for the case of "fair weather", is shown in figure 5. Similar nature of the temporal course of the total value of global current density $j_I(t)$ and the derivative of the field strength $(dE(t)/dt) = f(t)$ indicates the dominant role of the displacement component $(dE(t)/dt)$. Similar nature of the obtained time characteristics seems to confirm (in this particular case – time course and low conductivity current component) the internal consistency of results of measurements as well as measurement technique applied.
**Figure 4.** The intensity of the normal component of electric field $E(t)$ at the measuring electrode-collector, determined from the relation (5). The average value of the field strength during the registration (approx 10 min), $E = 209$ V m$^{-1}$. Results obtained for a sunny day with transient small clouds (05.10.2011).

**Figure 5.** Time variation of the average electrode current density $j_T(t)$ and the time derivative of the average intensity of electric field $dE(t)/dt$ at the measuring electrode. Results obtained for a sunny day with transient small clouds (05.10.2011). Current density average value $j_T = 2.7$ pA m$^{-2}$.

**Figure 6.** Time variation of air conductivity $\sigma(t)$ in the region of measuring electrode. The conductivity average value (for the period of 600 s) $\sigma = 16.6$ fS m$^{-1}$. Results obtained for a sunny day with transient small clouds (05.10.2011).
The air conductivity $\sigma(t)$ time variation (which can be considered as a parameter of air quality), received from the formula (3) is shown in figure 6. The result indicates that the conductivity $\sigma(t)$ may vary in relatively wide limits. Negative values of $\sigma(t)$, obtained for certain time periods, may result from different reasons. The reasons include: 1) errors resulting from the small difference of large numbers (a small component of the conductivity current in the total current value), 2) transient space charge ("clouds of ions"), 3) emission of electrons from the electrode-collector during it exposure to direct sunlight (UV) (when not screened by clouds).

The obtained results (for global current density and electric field strength) indicate the need to correlate them with the local (in the vicinity of the collector) measurements of ion density and light intensity, especially in the UV region.

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References
[1] Harrison R G 2011 J. Phys. Conf. Ser. 301 012001
[2] Singh D, Gopalakrishan V, Singh R P, Kamra A K, Singh S, Pant V, Singh R and Singh A K 2006 Atmos. Res. 84 91
[3] Markson R, Ruhnke L H and Williams E R 1999 Atmos. Res. 51 315
[4] Czapka T, Dymczyk J, Kacprzyk R and Seredyńiecki W 2011 Transducer for the measurements of dc and low frequency electrical fields. Raport nr I-7/SPR-5/2011, Institute of Electrical Eng. Fundamentals, Wroclaw Univ. of Technology, Wroclaw 2011 (in Polish)