Atmospheric Electricity, Geological Heterogeneity and Hydrogeological Processes †

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Abstract: Elements of surface atmospheric electricity have never been used to solve problems of applied geophysics. A physical model representation of hydrogen, methane, radon, and elements of surface atmospheric electricity is constructed. Bubble formations of volatile gases capture from the depth of 4–6 m soil radon and carry it into the near-surface layers of the soil and atmosphere. The increase in the density of carrier gases over the ore body, oil field, fault zones, karst cavities leads to a fall in the atmospheric electric field and an increase in the polar air conductivities. The pumping of artesian water causes an increase in the atmospheric electric field. The injection of fluid into the ground leads to the reverse process—the fall of the atmospheric electric field.

Keywords: hydrogen; methane; radon; atmospheric electric field; polar air conductivities

1. Introduction

According to the theory of surface atmospheric electricity, the main ionizer of near-surface air is the exhalating soil radon [1–3]; radon transport through the rock occurs at a speed of 40–60 cm/day [6]. However, the high molecular weight of the radioactive gas is 222, which excludes the possibility of its isolated subvertical migration with similar velocities into the near-surface layers of the soil and the atmosphere. For a long time it was believed that all volatile gases of soil air are carriers of radon into the near-surface layers of the soil and the atmosphere [4–6]. However, recent experiments have shown that the transfer of radon is accomplished by bubble formations of only two gases—hydrogen and methane [7–9].

The presence of radon in the earth's crust will be determined by the spread of maternal matter. According to the Biogeochemical Laboratory of Academician V.I. Vernadsky, the content of radium in soils is only an order of magnitude lower than in the rock. In particular, in clay, the average content of radium is 1.3×10^{-10}%, which is only half as much as in granites 2.58×10^{-10}% [10].

The obtained material makes it possible to construct a model of hydrogen-methane-radon and atmospheric-electrical bonds between the fields of the Earth and the atmosphere. The subvertical flow of hydrogen and methane captures radon from a depth of 4–6 m and carries it to the near-surface layers of the soil and the atmosphere [11,12]. The light ions produced in the ionization process determine the polar conductivities of the air—PC; their recombination with neutral condensation nuclei sets the atmospheric electric field—AEF. The negative charge of the Earth leads to an electrode effect. With an ionizer deficit, the classical electrode effect takes place—a smooth drop in the field with an exit to the normal background level; when there is an excess, a reversible electrode effect is observed—a drop in the field, an inflection and subsequent growth to the background level [9]. The results and experiments of the recent years demonstrated that the most contrast variations in AEF that resulted from the changes in the regime of soil radon exhalation are

observed at the height from the first decimeters to 2–3 m that was taken into account in all described observation cycles.

We will conduct a rough illustrative assessment of the sensitivity of surface atmospheric electricity elements to the regime of soil radon exhalation. The radon content of the soil is not less than 100 times higher than the atmospheric radon content [13,14]. Within the framework of the model under consideration, this means that elements of surface atmospheric electricity are extremely sensitive to the density of the subvertical flow of hydrogen and methane.

Let us consider a series of experimental studies illustrating contrast changes in elements of surface atmospheric electricity over geological heterogeneities and zones of geodynamic processes.

2. Instruments and Methods of Observations

The RGA-01 sensor allowing the registration of volumetric activity of radon in the range of $2 \times (10^{-2}–10^3)$ Bq/L was used for all measurements. The relative error of single reading is ~30%. The experience of multiyear operation of the mentioned sensors enabled developing the optimum technique of observations. The minimum time loss and the maximum accuracy are reached by taking four readings in each sample. The first reading is taken for the time period of 200 s; over that time the thoron concentration in the sample decreases by a factor of ten (the half-life of thoron $\tau_{Tn} = 57$ s). The next three readings are taken for the periods of 20 s. The above four consecutive readings reduce the time of temperature drift of the fluorescent cover that leads to the higher reliability of results. The volumetric activity of radon in the sample is computed by averaging 2–4 readings. The error in the determination of the volumetric activity of radon in each sample after the averaging is reduced to 17%.
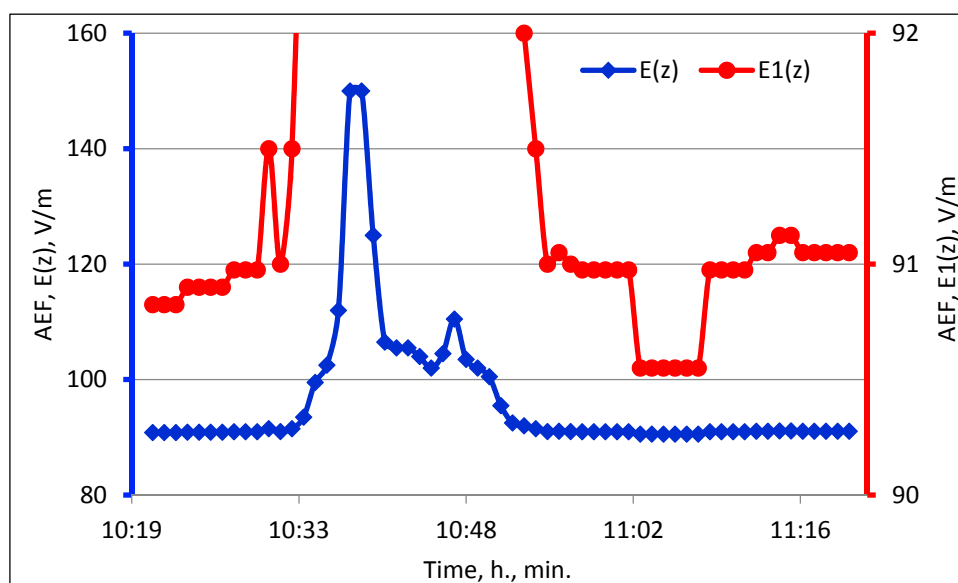
The sensors of the volumetric activity of radon was certified in the Laboratory of Metrology of Radiometric Measurements of the Russian Research Institute of Physical, Technical, and Radiotechnical Measurements in Moscow before the field works and after them. The parameters of measuring Instruments remained stable over the period of field measurements.

The atmospheric electric field was registered with «Pole-2» and «Gradient» field mills developed and produced by the Main Geophysical Observatory (MGO). The instruments provide the long continuous operation, have two automatically switch able measurement subranges (500 V/m and 5000 V/m) with the relative error of 5%, and allow the operational absolute calibration by connecting an external source for inducing the reference electric fields of operating range in the area of measuring plates.

All described measurement cycles were conducted under good weather conditions. Never the less, the profile works were always accompanied by the continuous control of temporal variations in atmospheric electric field with the «Pole-2» stationary field mill. In particular, the dramatic increase in the electric field up to 150 V/m was registered at 10:31–10:55 on 10 June 2004, whereas before and after that the atmospheric electric field varied in the limits of the instrument measurement error and was equal to about 91.5 V/m, Figure 1.

The registered variations in the field were the effects of dew evaporation as a result of solar heating, namely, of the injection of neutral condensation nuclei to the surface atmosphere that caused the dramatic increase in AEF. The results of profile measurements for that time period were excluded from consideration and the observation instruments were polled once again after the stabilization of the field back ground level.
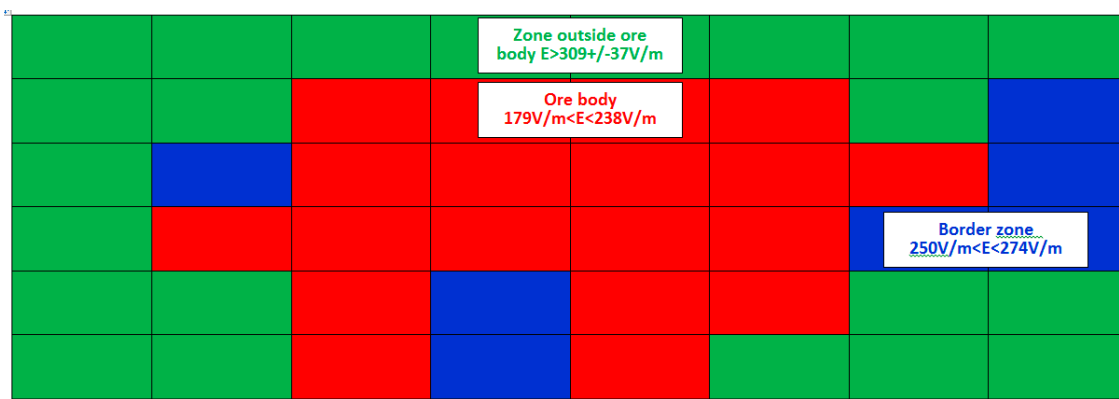
Polar air conductivity registered by using aspirating block capacitors. The relative error of measurement ~10%. For the production of field work, the measuring instrument was converted to a 12 V battery.

Figure 1. Increase in atmospheric electric field recorded with a stationary fluxmeter on 9 June 2005; the mean background level is 90 V/m; the maximum amplitude is 150 V/m; E(z) and E1(z) records on small and large scales, respectively.

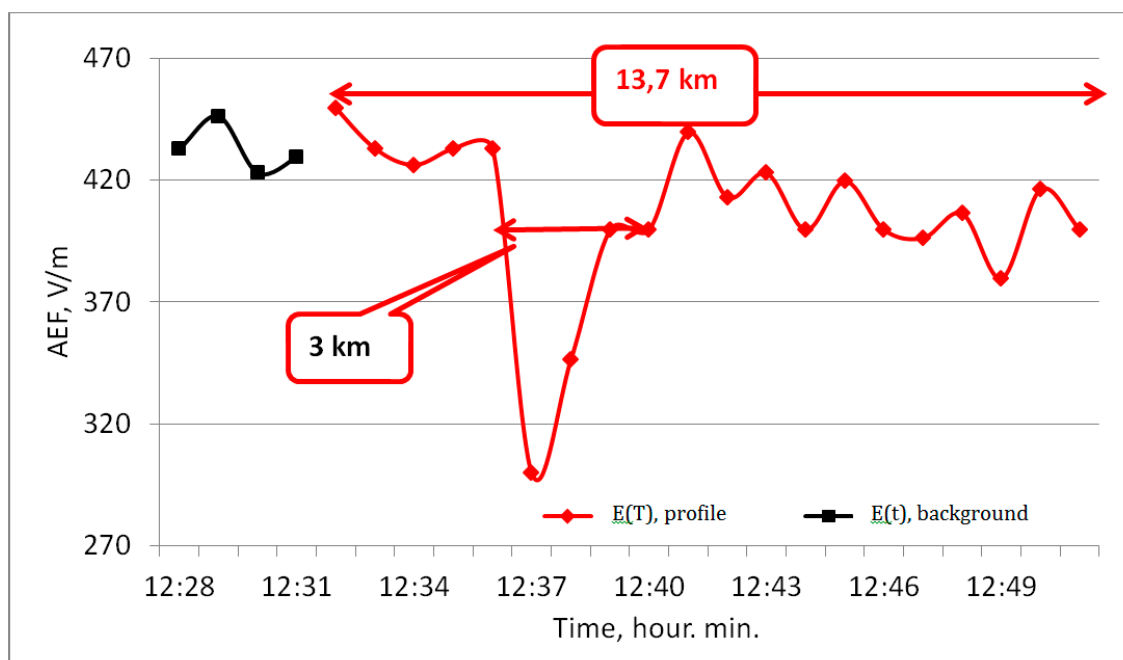## 3. Atmospheric Electric Field over Geological Heterogeneity

For the first time, AEF changes over geological heterogeneity were registered in June 1986 over the ore-body. The measuring profile passing approximately through the investigated deposit centre. Over the area of the ore-body has been registered decline of the AEF ~ 60 V/m [15]. The experiment was repeated in August 1987 to 11 observation profiles [8]. The results of observations are presented in Figure 2.

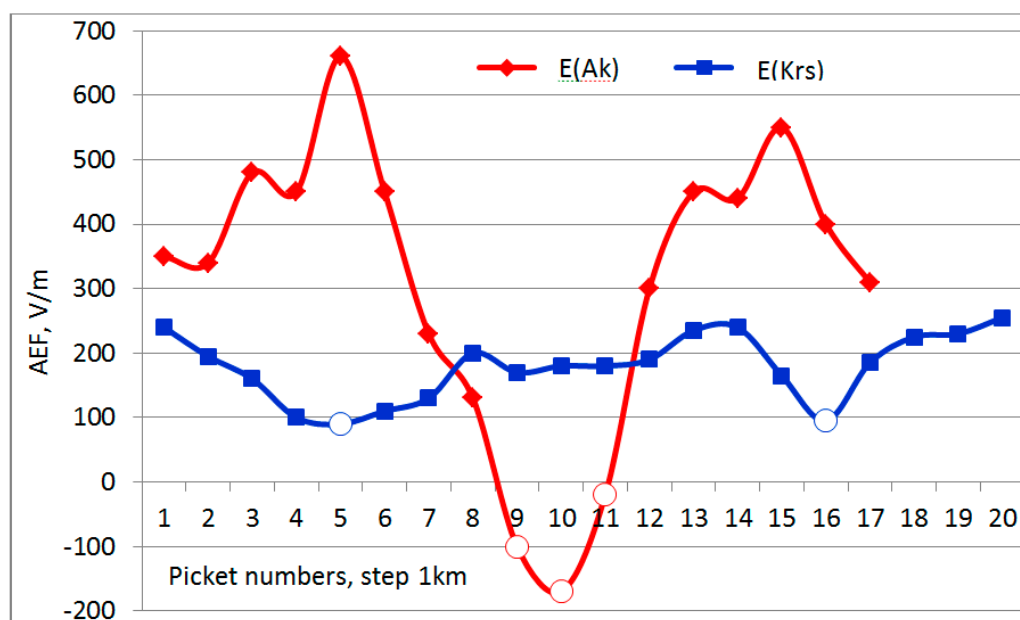**Figure 2.** Some examples of variations of AEF over ore-body in 1987.

The reason for the observed decline AEF—hydrogen formed at the top of the ore-body at the expense of electrochemical processes.

A close result was obtained on the profile with a total length of 13 km where was found the sharp increase in the thickness of sedimentary rocks—Figure 3.

Figure 3. Variations of AEF over the zone of sharp increase in the thickness of sedimentary rocks.
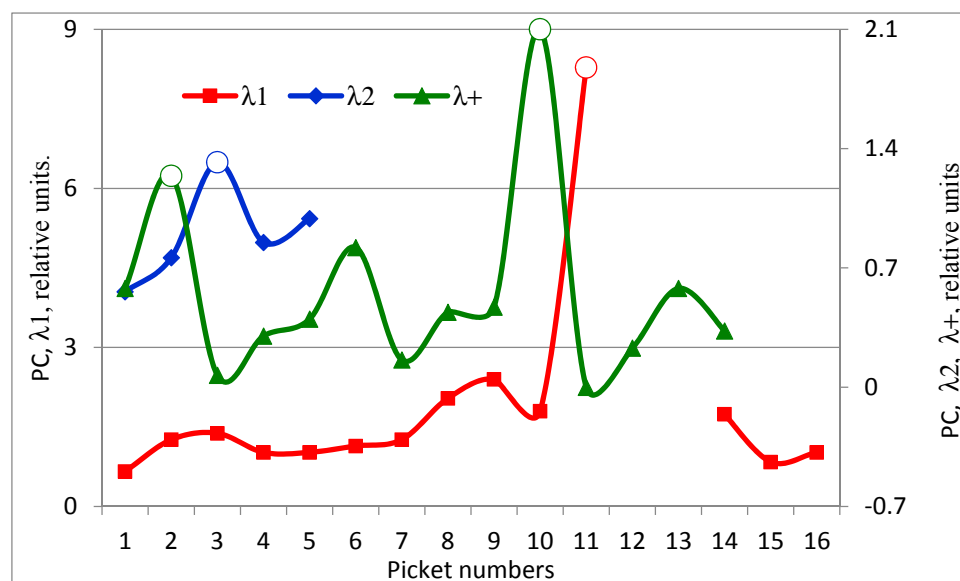
Registered a decrease of the field is a consequence of the increased gas permeability in sedimentary rocks. The growth of the flux density of hydrogen and methane will inevitably lead to an increase in radon exhalation. A similar increase of the flux density of hydrogen and methane has place in fault zones. In Figure 4 examples of recession AEF over fault zones of Aktash River area (Dagestan) and Kaluga ring structure [8,16]. The minimum values of AEF are marked with circular markers.

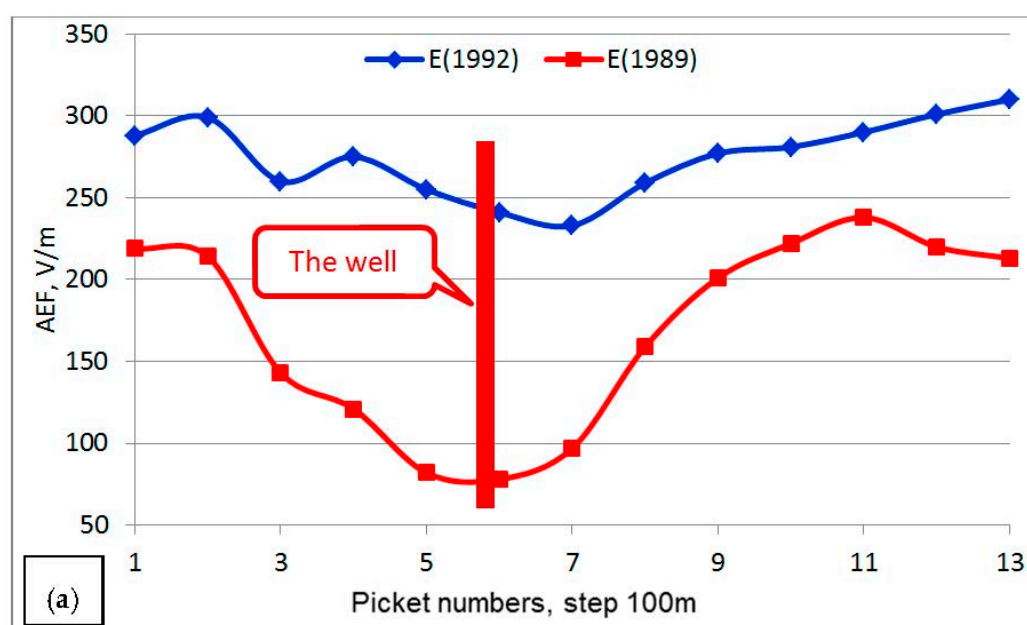**Figure 4.** Variations AEF in faults zones: Aktash River area E(Ak), Dagestan; Kaluga ring structure E(Krs).

The same result can be observed in variations of the polar conductivities of the atmospheric air over the regions of decompaction of the earth's crust [17]. In Figure 5 presents the data of profile observations of PC in the "cross" with metro lines of shallow and deep laying—$\lambda 1$, $\lambda 2$ and on the
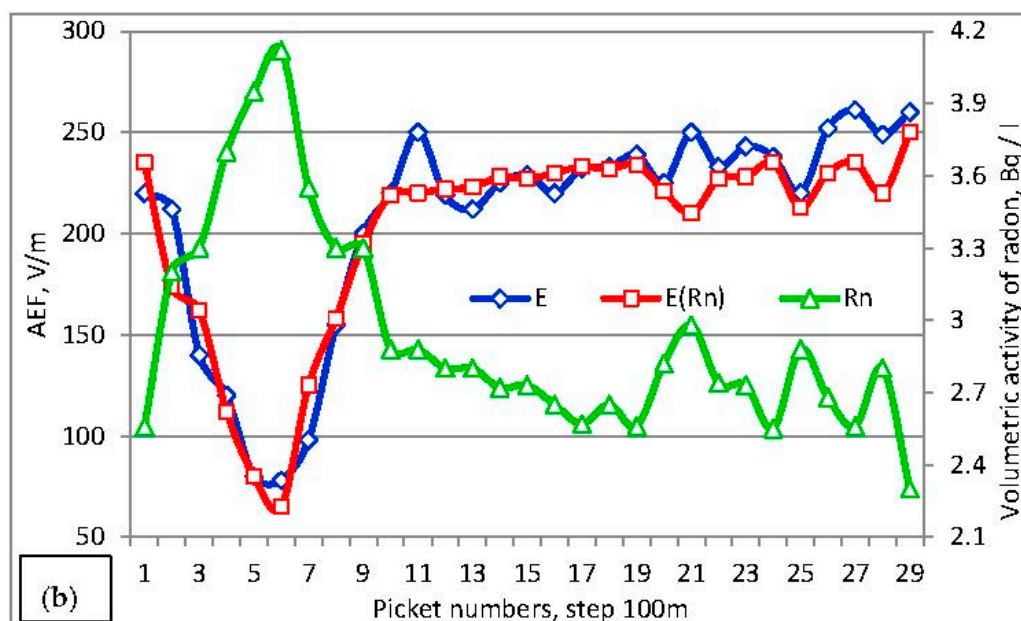
horseshoe profile that crosses the karst cavity twice—$\lambda+$. Pickets over the intersection of profiles with metro lines and a karst cavity are marked with circular markers.

Figure 5. Variations in the polar conductivities of air during observations: on the profile in the "cross" with a line of subway metro—$\lambda 1$, metro Kon'kovo, observation step 4 m; on the profile in the "cross" with a deep underground line—$\lambda 2$, Metro University, observation step 12 m; on the horseshoe profile, twice crossing the karst cavity—$\lambda+$ (Tula, Soyuzny lane), the observation step is 4–12 m.

A small subvertical flow of methane is present in plumes of oil deposits [18,19]. At the 3rd Rechitsa oilfield (Belarus) at the new production well in 1989 and 1992, profile AEF observations were made twice: E(1989) and E(1992) Figure 6a. For 3 years the decline of the field over the oil deposit has significantly decreased due to a decrease in in-situ pressure and flooding of the formation.
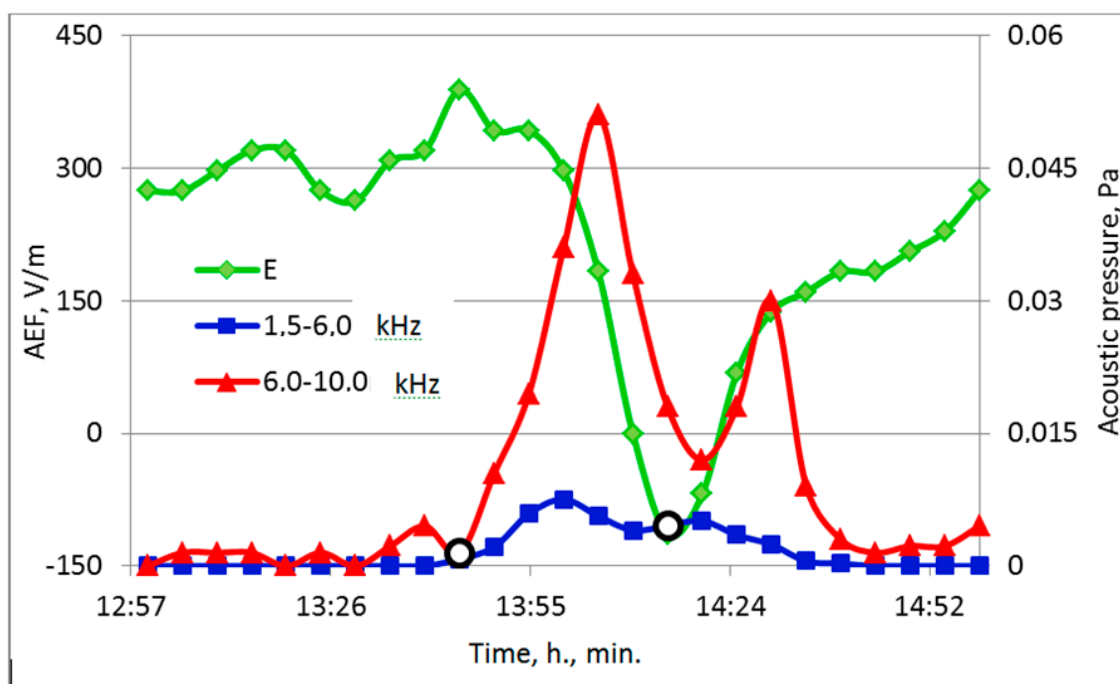
Figure 6. Variations of AEF—E(1989), E(1993) near the well on the 3rd Rechitsa oilfield (**a**); Variations of AEF—E, E(Rn) and volume activity of ground radon—Rn on the Aleksandrovskaya oil deposit (Belarus) (**b**).

The same was observed at the Aleksandrovsky oilfield (Byelorussia)—Figure 6b. Simultaneously with observations of AEF—E, the volumetric activity of ground radon, Rn, was recorded at observational pickets. The arrays of observational data were divided into two parts—above the deposit and outside the reservoir, and linear approximations of AEF were constructed, as functions of volumetric soil radon activity—E(Rn). The reliability of the approximations is ~0.8. The reason for the decay of the AEF is the methane of the plume of hydrocarbons over the deposits. In addition to oil deposits, methane is present in the plumes of artificial underground gas storage facilities—UGS, which naturally leads to the decline of AEF [7,18,19]. So on the territory of the Shchelkovo PHG, according to observations on 11 profiles in 1999, the average AEF over the injection volume was $E_v(1999) = 284$ V/m. Outside the projection area of the injection volume to Earth $E(1999) = 557$ V/m. According to the results of the 2000 observations, the mean values of $E_v(2000) = 368$ V/m, outside the injection zone AEF $E(2000) = 599$ V/m. At the Kasimovskorm PHG, the average values of AEF for injection volume $E_v = 138$ V/m; outside the injection volume $E = 184$–240 V/m.

North-Stavropol UGS is located in plast-collector of the former North-Stavropol deposit, i.e., where there was a natural accumulation of combustible gas. Here, the average field values over the injection volume at $\Delta E = 79$ V/m are greater than beyond.

3. Elements of Surface Atmospheric Electricity over Zones of Geodynamic Processes

During observations of acoustic noises in the range 1–10 kHz and AEF, the field decay was observed with a sign change after the noise level increased by many orders—Figure 7 [20]. Because of the powerful release of radon into the atmosphere, the field changes sign—the reversible electrode effect. Minimum values of the field are reached in ~30 min after the beginning of growth of seismoacoustic noise—at the middle of the lifetime of heavy ions.

Figure 7. Decay of AEF as a result of a sharp increase in the pressure of seismoacoustic noise in the ranges 1.5–6.0 kHz and 6.0–10.0 kHz [20].

In December 1992, in the vicinity of the city of Sasovo (Ryazan region), profile AEF observations were made. One of the profile with a length of ~1000 m was approached at an angle of ~30° to the shunting tracks, on which the continuous formation of railway trains proceeded.

The records of the background level of the field near the railroad track and its variations in the passage of the profile from the railroad track and to the railroad track are given in Figure 8a. Relatively low AEF values for the railway and its subsequent growth when moving along the profile by ~200 V/m are determined by the high level of technogenic seismic noise generated by the movement of the rolling stock. The frequency range is 5–25 Hz, the amplitude of the oscillations is tenths of a millimeter, which is 3–4 orders of magnitude higher than the background level [21,22].
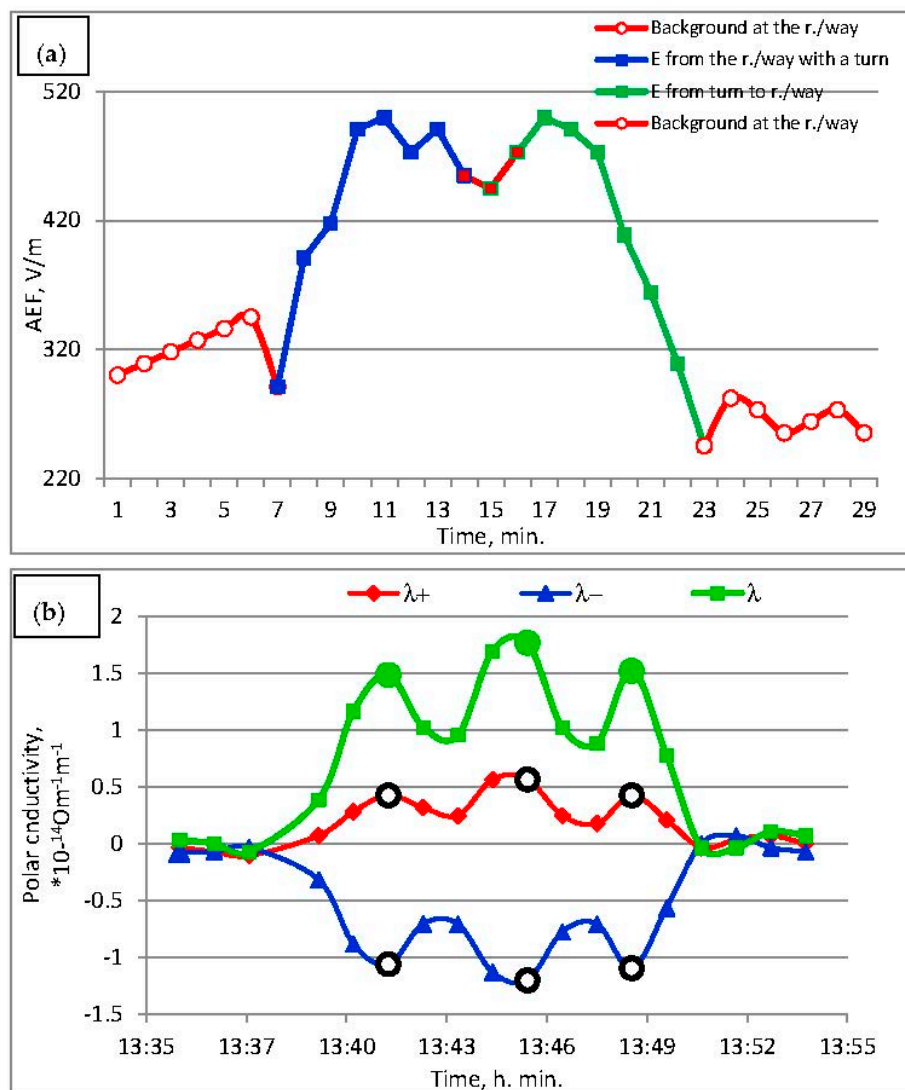
A similar result was observed when registering the polar air conduction over the underground line of a deep deposit—about 25–30 m—the middle of the distance from the metro bridge on the Vorobyovy Gory to the University station—Figure 8b. Here, a 10-min continuous recording of positive and negative PC was made. Due to the growth of seismic noise during the passage of trains, there is an almost twofold increase in signal levels.

Temporal variations of positive, negative and total PC over the metro line. Intervals 13 h 35 m–13 h 39 m and 13 h 50 m–13 h 54 m—record zero level of the PP; 13 h 41 m, 13 h 45 m and 13 h 49 m—the passage of the metro trains under the observation picket (b).

Consider data from profile observations of the AEF over the depression funnel of the city water intake station (the depth of the operational horizon is about 80 m at a power of the order of 30 m, Svetlogorsk, Belarus) [8,21,22]—Figure 9.
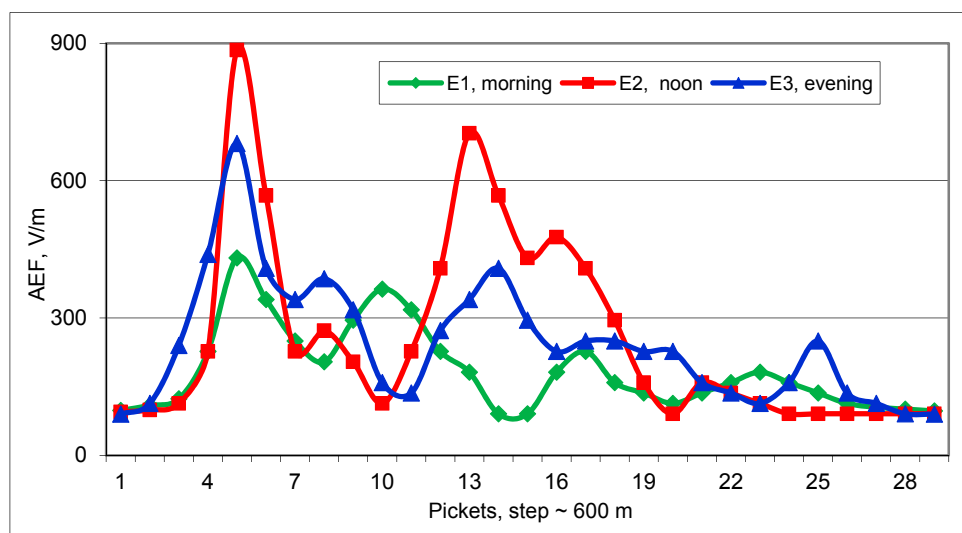
Peak values of the field on the traverse of the intake station in the morning, noon and evening reach values of ~(400, 900 and 600) V/m. The reason for this is the depression funnel formed in the reservoir during the water intake and extended in the direction of Svetlogorsk-Uznozh, minimizing air-soil air exchange and leading to the field growth—the classical electrode effect.

In Figure 10 shows the temporal changes in the field, registered with the reverse procedure—when injecting fluid into the soil.
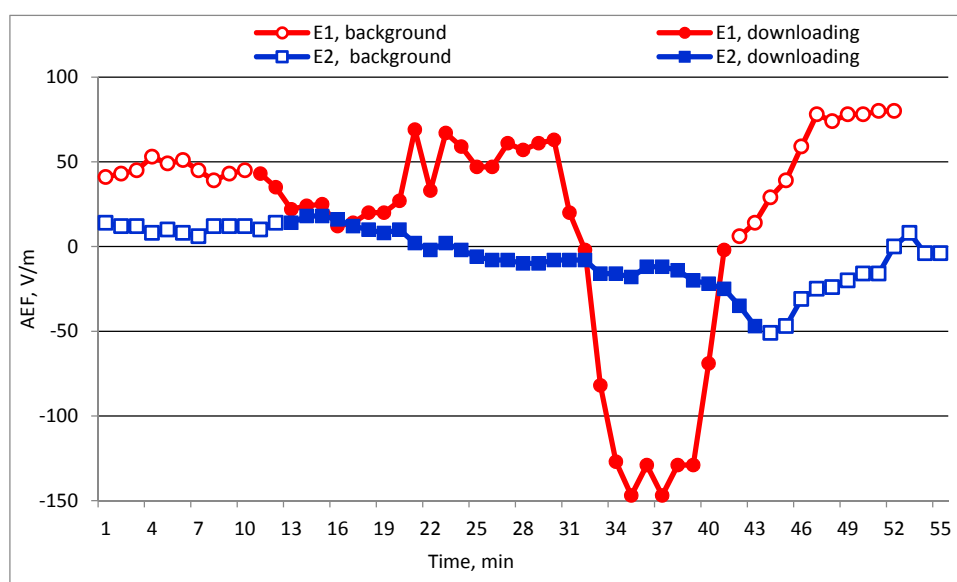
Figure 8. Background of the AEF near the railway; variations of AEF on the profile from the railway—E (from railway) and to the railway—E (to railway) (**a**); Temporal variations of positive, negative and total PC over the metro line. Intervals 13^h35^m-13^h39^m and 13^h50^m-13^h54^m—record zero level of the PC; 13^h41^m, 13^h45^m and 13^h49^m- the passage of the metro trains under the observation picket(**b**).

Figure 9. Spatial variations of the AEF on the Svetlogorsk-Uznozh highway over the urban water intake zone.

Figure 10. Variations of the atmospheric electric field during 1 and 2 cycles of pumping 30 m³ of fluid into the ground to a depth of 50 m.

A sharp drop in the signal with a change in the sign of the field is evident to values of the order of [(−140)–(−50)] V/m somewhere in the 20th minute from the start of injection. The reason for this—a powerful local release of the ionizer at the time of formation of hydraulic fracturing—the reverse of the classical electrode effect.

Re-injection of 30 m³ of water into the fracturing zone almost caused similar changes in the field at the mouth of the injection well, but, naturally, at smaller amplitude changes. If during the first injection the ratio of the minimum negative fields to the background before the start of the cycle was ~(−4), in the second case it was ~[(−4)–(−5)]. During the first and second injection, the minimum signal is observed at the middle of the lifetime of heavy ions. A similar result is shown in Figure 8 [20], where the stimulus for the release of radon was an increase in the level of seismoacoustic noise.

4. Conclusions

The established relationships between surface atmospheric electricity elements, radon, hydrogen, and methane, and the presented field observations make it possible to state that the changes in the AEF and PC of air over geological inhomogeneities will be determined by variations in the density of the subvertical fluxes of the listed volatile gases. There are several reasons for these changes:

- growth of gas permeability of rocks in the zone of heterogeneity: fault zones, increase in the thickness of sedimentary rocks, decompaction of the earth's crust (underground engineering structures, karstic cavities), leading to growth of PC and AEF decline;
- presence of a small subvertical flow of hydrogen or methane over the geological heterogeneity: iron ore deposit, oil deposit, underground gas storage, cause AEF decline;
- natural gas deposits possessing high-tight tires, on the contrary lead to a decrease in the density of subvertical flows of hydrogen and methane, which is accompanied by the growth of AEF.
- In addition to the geological features of the structure of the earth's crust, the geodynamic processes will affect the ionization of near-surface layers of air:
- seismic noise of natural and man-made nature stimulates air-soil-atmosphere air exchange—growth of PC and AEF decline. The effectiveness of the impact will increase with the fall of the oscillation frequency, and reach a maximum under deformations;
- an increase in groundwater level will lead to an increase in soil radon exhalation—growth in PC and AEF decline; the decline in the levels to the reverse process—to the decline in PC and the growth of AEF.

Executed assessments and materials of field observations clearly illustrate the possibility of using elements of surface atmospheric electricity for solving applied geophysical problems.

Conflicts of Interest: The authors declare no conflict of interests.

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