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# AN EXPERIMENT TO EXAMINE THE COVARIATION OF ATMOSPHERIC ELECTRICAL VERTICAL CURRENTS AT TWO SEPARATE STATIONS

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Abstract. Simultaneous recordings with long-wire antennas of the air-earth current density at two stations, 13 km apart, on the latitude of 60°N are presented. The covariation of currents was identified in conditions of a cloudless atmosphere and low turbulence of the air. The common component of recordings is interpreted as ionosphere-induced variation of atmospheric electrical vertical current density. Long-wire antennas spaced a few kilometers apart can be recommended as instruments for measurements of the ionosphere-induced variations in wintertime and in high latitudes.

## 1. Introduction.

The general objectives of the experiment have been proposed by the Global Atmospheric Electricity Measurement (GAEM) Program (Michnowski and Ruhnke,1991). An essential topic of GAEM is separation and identification of local, global and extraterrestrial effects in surface measurements. A mediator of global and extraterrestrial effects in atmospheric electricity is the ionosphere. Ruhnke (1969) has pointed out that the fair-weather Maxwellian vertical current density on the surface level follows the variations of the ionospheric potential. The word "Maxwellian" is omitted below but the Maxwellian current is assumed everywhere in the present paper when the atmospheric electrical vertical current is discussed. A long wire antenna was proposed by Ruhnke as an instrument for measurement of vertical current density. In addition to the ionospheric effect, a fluctuating component of local origin is always present in the signal of an antenna. The identification of an ionosphere-induced component in the measured signal is a key problem of surface measurements of global and extraterrestrial effects in atmospheric electricity. Both the design of measurements and the signal analysis are essential factors of the success.

The existence of the short-period global variations of vertical current density was demonstrated using two antennas separated by thousands of kilometers (Ruhnke et al., 1983). The objective of the present research is to examine the possibility of identification of ionosphere-induced effect using two antennas separated by a distance of ten-kilometer scale.

## 2. Components of atmospheric electrical vertical current variation.

Variations of the atmospheric electrical vertical current density consist of three main components:

- turbulence-induced variations,
- cloud-induced variations,
- ionosphere-induced variations.

Variations induced by surface layer convection are not distinguished from the turbulence-induced variations. The root of the turbulence-induced variations is the inhomogeneity of the space charge density in the electrode effect layer ( Yerg and Johnson, 1974, and Israelsson and Knudsen, 1983). The "clouds" of space charge driven by wind near the surface are stimulating the fluctuating displacement current on the antenna. Typical frequency of variations is a few cycles per minute. The height of the electrode effect layer is from a few meters to tens of meter. The same scale is expected as characteristic of the spatial correlation of the turbulence-induced variations. The measurements by Ruhnke (1969) and Tammet (1991a) confirm the assertion. The signals of parallel antennas separated by a distance of 85-325 m were measured in the last investigation. A very low correlation between the signals of two antennas was detected in case of distance of 85 m and no covariation of short-period variations was identified in the case of a longer distance.

The spatial scale of cloud-induced variations is estimated from a few kilometers to hundreds of kilometers. Rapid variations of large spatial scale can be generated only by discharges in thunderstorm clouds. Currents induced in two-spaced antennas by the horizontal movement of a non-thunderstorm cloud are shifted in time suppressing the covariation of the synchronous signals. The cloud-induced variations are not expected to be observable in a situation of visually cloudless weather. The negotiation of covariation in measurements described by Tammet (1991a) is confirming the conclusion.

Two subcomponents can be considered discussing the ionosphere-induced variations. The first component caused by variations of the average potential of the whole ionosphere can be called the global component. A well-known example is the Carnegie curve consisting of very low frequency harmonics of the diurnal cycle. Short-period variations of the average ionospheric potential can be caused by fluctuations of global thunderstorm activity. The effect is estimated to be low and difficult to identify on the background of turbulence-induced variations.

Variable electrical currents in the upper atmosphere are the root of the second component of the ionosphere-induced variations. The sources and characteristics of currents in the upper atmosphere, corresponding ionospheric potential variations and the downward mapping of ionospheric electric fields toward the lower atmosphere are discussed, e.g. by Volland (1984) and Roble (1991). The second component is of regional character and it can be called the regional ionosphere-induced variation. Typical regional variations of ionospheric potential in high latitudes exceed tens of kilovolts. The corresponding variations of the vertical current density on the ground level are theoretically estimated up to 1 $pA/m^2$ and even more in geomagnetic storm periods. We assume that spatial and temporal correlation scales of the subcomponent are nearly the same as in the case of a visual aurora.

## 3. Problem of ground level identification of ionospheric potential variations.

The short-period ionosphere-induced variations of the vertical current density were tested by Ruhnke et al. (1983) using two large- area wire antennas in mid-latitudes spaced about 7,000 km apart. An extra long distance was considered as a reliable warranty of elimination of non-ionosphere-induced covariations in the experiment. The distance excees the spatial scale of the regional ionosphere-induced variations. The lag up to 40 seconds was observed comparing the signals recorded by two antennas, and it caused complications in when interpreting the results.

The lag between the signals of two antennas should be suppressed, and the interpretation of measurements should be simplified when the distance between the two antennas is less than the effective height of the ionosphere.

The main complication of the short-distance two-antenna experiment is the requirement to avoid the effect of cloud-induced variations. A distance about 13 km was used in the present measurements. The distance is big enough to avoid the short-period covariations caused by turbulence and non-thunderstorm clouds. For the sake of reliability the present measurements were carried out only when no clouds were observed in the neighborhood.

## 4. Experimental arrangement.

The measurements have been made at the Marsta Observatory and Ultuna Agriculture University (59°55'N, 17°35'E) near Uppsala, Sweden. The observation sites are 13 km apart from each other. The distance is sufficient to avoid the turbulence-induced covariation and the cloud-induced covariation in a situation of low electrical activity of clouds. Both stations are located in very flat farming country areas: Marsta 8 km north of Uppsala, and Ultuna 5 km south of Uppsala. The nearest forests are more than 1 km away from the measurement sites. No industrial establishments by which condensation nuclei might be produced are in the surroundings of the observation places. A map of the Marsta Observatory is presented by Israelsson et al. (1973).

The principle of measurement is shown in Fig. 1. Two equivalent long-wire antennas and electrometric amplifiers were installed on the two stations. Each antenna was 100 m long placed at a height of 3 m over a plain surface of a wide-open field. The only disturbing obstacles in the neighborhood of the antennas were the buildings of measurement stations. The long-wire method is described in previous similar projects by Ruhnke (1969), Ruhnke et al. (1983) and Tammet (1991b). The effective area of an antenna in the present experiment was 210 $m^2$. The antenna insulators were made of teflon and equipped with the heating elements. To prevent contamination, the insulators were kept indoors between the recording periods.

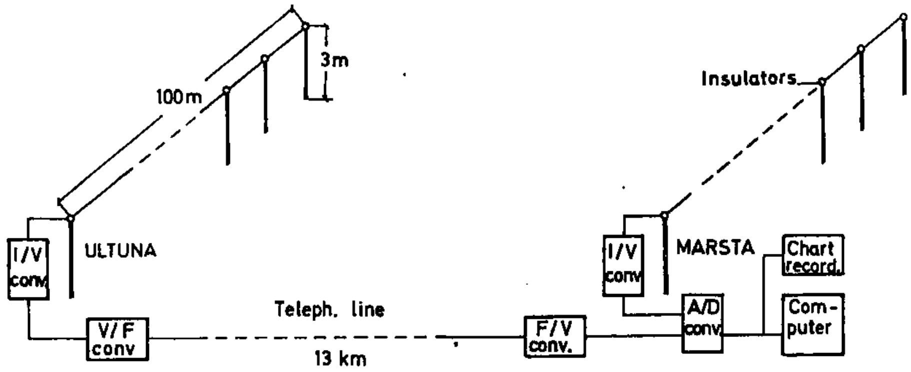

Fig. 1. Experimental setup at the two recording stations Marsta and Ultuna.

Equivalent electrometric operational amplifiers were used to convert the current collected by an antenna to the voltage in both stations. The time constant of each amplifier was adjusted to 10 seconds. A common recording instrumentation placed in the Marsta Observatory was used to monitor and store the signals of both antennas. At the Ultuna station the signal was converted to a variable frequency by a voltage controlled oscillator (ICL 8038) connected to a miniature loudspeaker hooked on the earphone (not shown in the figure) of the telephone. The operating frequency range was adjusted to be between 500-1500 Hz for an input voltage range of -0.5 to +1 V. The frequency range was selected for the best transmission through the telephone line. At the Marsta Observatory, an equivalent loudspeaker used as a microphone was hooked to the telephone (not shown in the figure) and a frequency to voltage converter restored the signal.

Signals from both stations were conditioned in the A/D-converter for computer recording. The signals were converted and stored in a computer memory every second and written into disk files every hour. For operative information a simultaneously running two-channel chart recorder was used.

In the Marsta Observatory a system of monitoring of the meteorological and general atmospheric electrical parameters was continuously running. The micrometeorological parameters (wind, temperature and relative humidity) were recorded with standard instruments. The electrical potential gradient was measured using the radioactive collector at a height of 1 m and the electrical polar conductivities using two aspiration condensers of the Kasemir-Dolezalek type (Israel, 1971 and 1973) at a height of 0.5 m. The space charge density was recorded in a layer up to 1.2 m above the ground surface with a Faraday cage method (Israelsson and Knudsen, 1983). The output of the system was used for identification of the fair weather situation appropriate for the vertical current measurements.

When compared with the experiment by Ruhnke et al. (1983), the probability to have fair weather simultaneously in both station is enhanced due to the closely correlated meteorological situation in a short distance. It follows a possibility to apply strict requirements to the weather conditions.

## 5. Measurement results.

The identification of ionosphere-induced variations of the vertical air-earth current density is possible only in the case of extremely low effect of turbulence and clouds. Therefore, the period of weather conditions with clouds or phenomena producing significant local atmospheric electrical disturbances was not used for the vertical current measurements. In the present study the proposal for determination of representative recordings during the GAEM Project (Knudsen and Israelsson, 1991) was accepted. The data of continuous measurements of meteorological parameters, electric-field strength, space-charge density and electric-polar conductivities in Marsta Observatory were used for evaluation of the weather conditions. Eleven one-hour periods in February 08 and 09, in April 13 and in May 10 and 11 were selected for the vertical current measurements. The meteorological conditions during the selected periods were: no cloudiness, wind speed 2-4 m/s at the height of 10 m, wind direction from open field to the antenna, relative humidity 28-60%. In February, the ground surface was frozen and dry that limited the exhalation of radon and thoron and caused low ionization in the atmospheric surface layer and low air conductivity.

The procedure of measurements followed the scheme given in the previous section. All recordings consist of considerable vertical current density variations. The fluctuations are similar to those observed by Ruhnke et al. (1983). The spectral analyze shows that an essential component of the variations is of turbulence-induced origin, which leads to a need for a sophisticated statistical analysis of the data, presented in the next sections.

## 6. Preliminary analysis of the data.

The preliminary analysis is to get an overview of the data and to select the mostly correlated data segment for the final analysis.

The technique of segment correlation analysis recommended by Tammet (1991) is used to estimate the covariation of the two antenna signals. The problem is to prove the existence of a true correlation on the background of random fluctuations when the autocorrelation function of turbulence-induced background variations of the antenna signals is unknown. In the stage of preliminary analysis every one-hour recording period was divided into 30 two-minute segments. The idea of the segment correlation analysis is the non-parametric comparison of cross-correlation coefficients calculated for synchronous segments with cross-correlation coefficients calculated for asynchronous segments. If the length of a segment is greater than the autocorrelation scale, the cross-correlation coefficients of ansynchronous segments are considered as the measure of random variations of the calculated correlation coefficient.

The following statistics were calculated for every one-hour period:

1. Average vertical current density for both antennas.
2. Standard deviations of the vertical current density in every two-minute segment, and average segment standard deviations for the full-hour period for both antennas.
3. 812 remote segment-segment autocorrelation coefficients, where the signals of the same antenna are compared and the segments are shifted for 4 minutes or more, and the average of 812 calculated values.
4. 58 neighbor segment-segment autocorrelation coefficients, where the segments are shifted for 2 minutes, and the average of 58 calculated values.
5. 870 asynchronous segment-segment cross-correlation coefficients,where the signals of two antennas are compared and the segments are shifted for 2 minutes or more, and the average of 870 calculated values.
6. 30 synchronous segment-segment cross-correlation coefficients, and the average of 30 calculated values.

The results are presented in Table 1.

Table 1
Average statistics of the vertical current density time series divided into 30 segments

| | | | Vertical current pA/m$^2$ | | | | Segment-correlation % | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Marsta | | Ultuna | | Auto | | Cros | |
| No | Date | Time | Ave | St-dev | Ave | St-dev | Remote | Neigh. | Asyn. | Syn. |
| 1 | 08.02 | 11:41 | 1.99 | 0.44 | 2.66 | 0.73 | -0.6 | 0.8 | 2.0 | -4.2 |
| 2 | 08.02 | 12:45 | 2.04 | 0.33 | 2.68 | 0.69 | 0.5 | 4.9 | 0.6 | 10.8 |
| 3 | 08.02 | 13:49 | 1.55 | 0.29 | 2.53 | 0.64 | -0.9 | -2.7 | -0.4 | 2.3 |
| 4 | 09.02 | 12:19 | 1.12 | 0.20 | 1.55 | 0.46 | 2.4 | 1.2 | -2.6 | -4.7 |
| 5 | 09.02 | 13:24 | 0.95 | 0.26 | 1.54 | 0.42 | 1.4 | -3.7 | -1.7 | 8.6 |
| 6 | 13.04 | 10:24 | 1.62 | 1.11 | 1.56 | 1.13 | -0.6 | 5.6 | -0.3 | -8.0 |
| 7 | 13.04 | 11:28 | 1.56 | 1.06 | 1.38 | 1.21 | -1.6 | -11.3 | 0.2 | 3.0 |
| 8 | 10.05 | 10:40 | 1.43 | 0.91 | 1.29 | 0.49 | 4.7 | 6.3 | 2.9 | -1.4 |
| 9 | 10.05 | 11:48 | 1.11 | 0.76 | 1.02 | 0.85 | -1.3 | -2.4 | 0.0 | -2.9 |
| 10 | 11.05 | 09:58 | 1.42 | 0.50 | 1.52 | 0.70 | 0.7 | -11.3 | -0.9 | 1.7 |
| 11 | 11.05 | 11:02 | 1.28 | 0.61 | 1.34 | 0.72 | 3.5 | -4.4 | -1.6 | 7.3 |
| Number of values | | | 30 | 30 | 30 | 30 | 812 | 58 | 870 | 30 |
| Average of 1...5 | | | 1.53 | 0.30 | 1.35 | 0.59 | 0.6 | 0.1 | -0.4 | 2.6 |
| Average of 6..11 | | | 1.40 | 0.83 | 1.35 | 0.85 | 0.9 | -2.9 | 0.1 | -0.1 |

The average values of vertical current densities in two stations are not equal. It can be explained by different values of vertical column resistance in two stations situated in various directions from the town Uppsala. The difference in values of the standard deviation is a result of different character of the ground surface that is a factor of air turbulence and corresponding turbulence-induced variation. The differences are not essential in the analysis of covariation.

If the two antenna signals would truly be not correlated, the calculated values of the correlation coefficient would be fluctuating around zero with amplitude inversely proportional to the square root of the number of averaged values. A correlation can be treated as significant if the calculated correlation coefficient is big enough not to be interpreted as a result of random fluctuations. Statistical significance of the calculated correlation coefficients presented in the Table was tested using the Van der Waerden technique recommended by Tammet (1991a). The evidence of real correlation cannot be firmly proved for any of the full-hour time series presented in the Table using the described technique. In the case of the most expressive record no. 2 the correlation was proved to be on the significance level of 5%. However, the conclusion can be considered as a result of the selection of the sample: If we have 20 samples, any non-existing effect can be apparently proved for some sample on the formal significance level of 1/20 with a probability of 50%. However, the record no. 2 is considered to be most interesting one for the further analysis.

Various subintervals of the one-hour records were learned to find the sample showing maximum correlation. The 16 last minutes of the record no. 2 was found to be the most expressive and selected for the final analysis.

## 7. Analysis of the selected data.

The selected data consists of 960 every-second measurements in Marsta and the same amount of synchronous measurements in Ultuna during the period from 13:29 until 13:45 on February 8, 1993. The weather conditions were: no cloudiness and west wind, 2-3 m/s at the height of 10 m. The ground surface was frozen and dry.

From the continuous recordings of the atmospheric electrical parameters (field-strength, conductivity and space-charge density) we draw the conclusion that fair-weather electrical conditions were predominant.

A diagram of the vertical current densities in both measurement locations is presented in Fig. 2.

The covariation of the signals can easily be detected by visual comparison of the curves. Correct statistical testing of correlation is simple only when the autocorrelation of time-series under comparison is negligible. The condition can be satisfied choosing the length of a segment long enough to avoid essential correlation between the subseries of neighbor segments. The segment correlation coefficient is a correlation coefficient between the internal subseries of the segments. One minute was proved as a satisfying length of a segment in the case of the data considered. The scale of random fluctuations of the calculated one-minute segment autocorrelation coefficient was examined comparing the combinations of remote minutes (shift of two minutes and more). The 210 available remote one-minute segment autocorrelation coefficients (average value of 2.0%) demonstrate the scale of random fluctuations of the calculated correlation coefficient. The 30 available neighbor one-minute segment autocorrelation coefficients (average value of 2.8%) are still in the scale of random fluctuations. Therefore, the autocorrelation is considered as negligible when discussing the series of 16 one-minute segments.

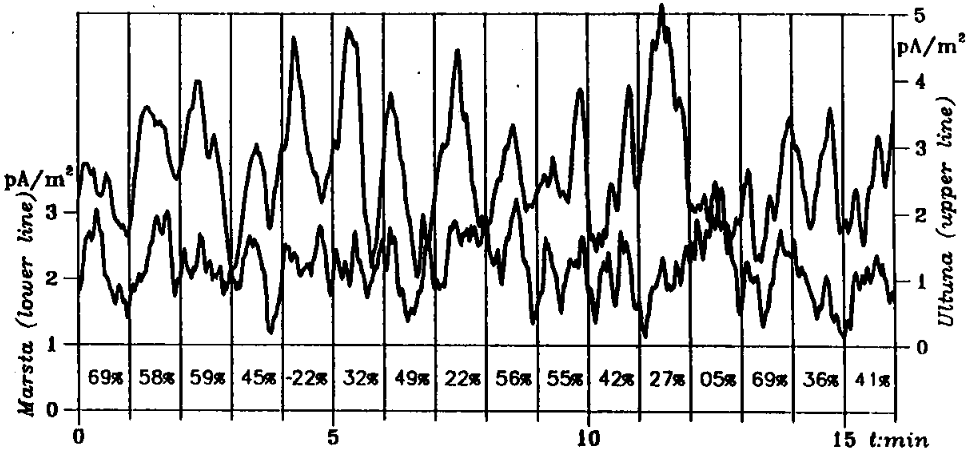

Fig. 2. Vertical current density measured using two 100 m wire antennas in Marsta and Ultuna (distance 13 km) every second during 13:29-13:45 on February 08, 1993 and the correlation coefficients between the measured currents calculated for every minute. Time constant of both measurement amplifiers is 10 s.

The average of 16 synchronous one-minute segment cross-correlation coefficients indicated in Fig. 2 is 40%. An estimate of random fluctuations was obtained calculating the 240 possible asynchronous cross-correlation coefficients. The average of calculated values is 3.5%. Various statistical techniques can be used to prove that the synchronous segment cross-correlation coefficients are high enough not to be explained as a result of random fluctuations. A simple and robust technique is the sign test that uses only the series of the signs of 16 segment correlation coefficients indicated in the figure. If any common component of two antenna signals does not exist, the probabilities of both plus and minus signs are 50%. It is easy to calculate that the probability to get 16 plus signs or one minus and 15 plus signs as a result of random fluctuations is $17*2^{-16} = 0.026\%$. The conclusion is: the zero hypothesis that the correlation coefficients indicated in Fig. 2 can be considered as a result of random fluctuations can be refuted using the sign test on the significance level of 0.026%.

We should not forget the preliminary procedure of the selection of the sample when testing the covariation using the full amount of the available data. The amount of data subsets examined during the preliminary analysis did not exceed one hundred. If the number is 100, the probability to get the above result because of random fluctuations for one subset is 100*0.026%. It follows, the existence of real covariation between the two antenna signals is proved on the significance level of 2.6% or with reliability of 97.4% using the considerations above.

An additional illustration of the covariation between the two-time series considered is presented in Fig. 3. The Lissajous figure is the equivalent of a traditional picture of correlation field, where the neighbor measurements are joined by a line. The regression path on the figure is diffuse due to the effect of non-correlated turbulence-induced variation.

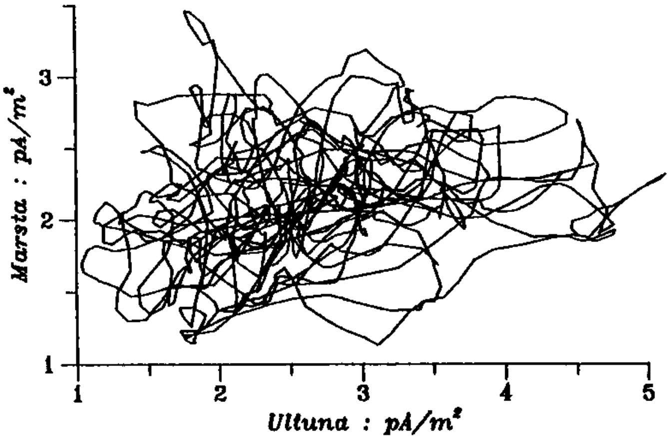

Fig. 3. The Lissajous figure of vertical current densities measured in two stations. The same data as in Fig. 2 is presented.

## 8. Discussion of results.

Let us consider the vertical current densities in both locations as the sum of the local component and the common component:

$$j_M = j_{Ml} + j_C, \qquad j_U = j_{Ul} + j_C,$$

and suppose that the three components are not correlated:

$$r\ (j_{Ml},\ j_{Ul}) = r\ (j_{Ml},\ j_C) = r\ (j_{Ul},\ j_C) = 0.$$

The standard deviation of the common component in the described model is

$$s\ (j_C) = \sqrt{r\ (j_M,\ j_U) * s\ (j_M) * s\ (j_U)}\ .$$

No clouds and no thunderstorm activity in the region around the antennas were observed during the measurements. The variations of the local component are interpreted as the turbulence-induced variations and the variations of the common component as the ionosphere-induced variations. Therefore, the above formula can be used to estimate the standard deviation of ionosphere-induced variations of the atmospheric electrical vertical current density in the present experiment.

Let us consider all the five-hour measurements in February

1993 first. The average calculated correlation coefficient is 0.026 and the standard deviations are 0.3 and 0.59 pA/m$^2$ for the two-minute segments. It follows that the estimate of standard deviation of the common variation 0.068 pA/m$^2$. As the value of correlation coefficient 0.026 is in the range of random variations, we can only conclude that the average standard deviation of the ionosphere-induced variations of the vertical current density during five hours is probably less than 0.1 pA/m$^2$.

In the case of the selected period 13:29-13:45 on February 8, 1993, the average calculated correlation coefficient is 0.4 and the standard deviations are 0.36 (Marsta) and 0.63 pA/m$^2$ (Ultuna) for the one-minute segments. The corresponding estimate of standard deviation of ionosphere-induced variations is 0.30 pA/m$^2$ and the estimate of turbulence-induced local variations in Marsta is 0.19 pA/m$^2$. It follows that the ionosphere-induced variations are dominating in the lower curve presented in Fig. 2.

The time-scale of the learned variations is about 10 s. The time constant of the air is less than 10 s at the height above 15 km. 10 s variations of the ionospheric potential are transferred mainly as the conduction current above 15 km and as displacement current below 15 km. The height of the upper conductive layer or "the electrostatic height of the ionosphere" is estimated at 15 km for the 10 second variations. The variation of the electric field of 0.34 V/m is required to induce the displacement current of 0.3 pA/m$^2$ during 10 s. The corresponding variation of ionospheric potential is about 5 kV. An upper atmosphere current of 0.3 A can provide the estimated variation on an area of 1000*1000 km$^2$.

## 9. Conclusions.

In the case of a cloudless atmosphere the ionosphere-induced variations of the atmospheric electrical vertical current density can be detected, and the ionospheric potential variations estimated using two long-wire antennas spaced a few kilometers apart.

The measurements in the latitude of 60°N demonstrated that in the case of a calm ionosphere the short-period ionosphere-induced variations of vertical current density are below of 0.1 pA/m$^2$ and could not be detected using the described technique.

The highest measured value of the standard deviation of ionosphere-induced variations of the vertical current density during 11 hours of measurements distributed in five various days was 0.3 pA/m$^2$. The indicated level of ionosphere-induced variations was recorded during 16 minutes on the background of turbulence-induced variations with the standard deviation of 0.19 pA/m$^2$ in the Marsta station.

Long-wire antennas spaced a few kilometers apart can be recommended as an instrument for the measurement of ionospheric potential variations in wintertime and in high latitudes, where the conditions are favorable for the recognition of the ionosphere-induced signal on the background of turbulence-induced noise.

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