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Technical Notes on Simultaneous Measurements of Atmospheric Electric Currents

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Abstract

The problem of identification of global variations on the background of local variations is considered using the results of special observations. Local variations were registered for this purpose in conditions similar to those occurring in the experiments in which global variations were attempted to be identified.

The results of special observations demonstrate that particularly confusing in the identification of global effects are quasi-periodical local variations, such as, e.g., phase-matches, which can cause apparent correlations between the signals of two antennas. The quasi-periodical local variations may be caused by a cell-structured convection of air, but also by mechanical vibration of the antenna, so the interference of the vibration and scanning frequency must be taken into account. The decision on the correlation of the signals of two antennas must not be made in a simple way on the base of the value of calculated correlation coefficient. A sound decision can be reached through juxtaposition of segments of simultaneous and time-shifted subseries by comparing the estimates of calculated correlation coefficients.

INTRODUCTION

The proposal of L.H. Ruhnke about the identification of short global variations in the signals of vertical current antennas (Ruhnke, 1969) has confronted the researchers with a number of crucial problems. The 1979 antenna experiment in Waldorf and

Vilsandi (Rhunke et al., 1983) has posed more questions than it has been able to solve. The last 20 years have everything but diminished the urgency of the problem. Thus, the technique and data analysis of observations deserve special attention.

The central technical problem is the identification of global variations on the background of local variations.

The nature and statistical modeling of local variations is an independent topic. At the latest international atmospheric electricity conference two papers were devoted to this topic (Anisimov, 1988; Makhdoomi and Raina, 1988). These papers contain references to previous investigations.

The identification of global variation, if at all, is possible only in the case of extremely low local variability. Therefore we are interested, first and foremost, in a statistical model of low local variability, rather than a general statistical model of local variations. The low variability situations find insufficient coverage in the literature.

In August-September 1988 the author conducted a series of special observations where local variations were registered in conditions near to those occurring in the experiments of the identification of global variations. Below the problems of technique of identification will be analyzed in view of the results of these observations.

THE DESCRIPTION OF THE OBSERVATIONS

The observation system was situated at the Matsalu Nature Preserve, the western coast of Estonia, $58^{0}47'06''$ N in latitude, and $23^{0}27'30''$ E in longitude. A field mill and three horizontal wire antennas were used as sensors (see Fig. 1).

A field mill "Pole-2" built at the Voeikovo Main Geophysical Observatory was used; the time of apparatus smoothing of signal was 1 s. The length of one antenna was about 50 m; the height was about 3 m; the diameter of the wire was 2 or 1.6 mm; the effective area was about 100 m^2. The antenna signal was amplified by an operational amplifier, the feedback circuit of which in most experiments contained

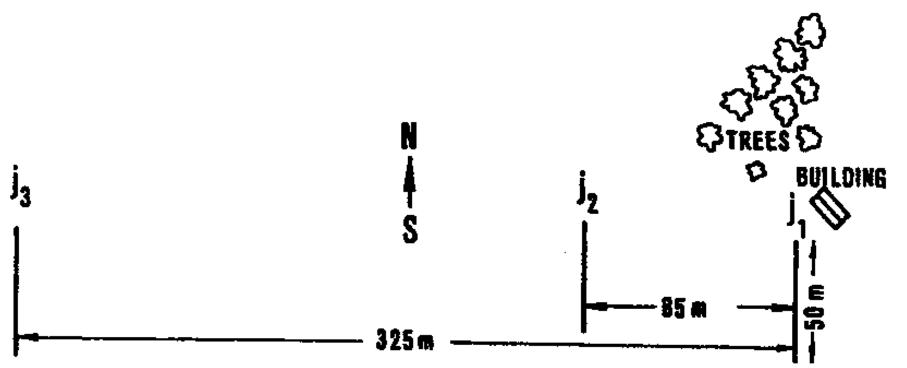

Fig. 1. The distribution of sensors on the seashore plain.

a 1000 MΩ resistor and a 1000 pF capacitor, which gives an apparatus time constant τ of 1 s. The current density $j_\tau = (t)$ obtained by the scaling of the output of the operation amplifier depends on the real Maxwellian current density $j_0(t)$ through an operator of exponential smoothing

$$j_\tau(t) = \int_0^\infty j_0(t - t') \exp(-t'/\tau) \; d(t'/\tau) \; . \qquad (1)$$

This formula can also be used for additional numerical smoothing of observation series.

The signals of all four sensors were recorded simultaneously with scan interval of 1 or 1.5 s. The time between the recording moments for different sensors did not exceed 0.06 s. In special observations only the signal from antenna 1 was recorded with a scan interval of 0.04 s, whereas the time constant of the amplifier of this antenna was set to 0.04 s.

The above observation system was switched on for periods when the conditions for the identification of global effects were favourable. The periods were defined on the basis of standard deviations of the density of vertical current. If the standard deviation of the signal of the stationary antenna 1 exceeded 3 pA/m^2, then the conditions were considered unfavourable and recordings were not made.

Below we will present a detailed analysis of the most favourable observation series.

Series A: time 88-09-07, 05:30-06:38 LT, 4096 measurements with 1 s intervals, clear sky, northern wind 2-3 m/s at a height of 2 m near antennas 2 and 3.1m/s near antenna 1, temperature 14°C, atmospheric pressure 1017 mb. Some data have been taken from another favourable observation series.

Series B: time 88-09-06, 18:35-20:17 LT, 4096 measurements with 1.5 s intervals, 40% of sky covered with thin middle altitude clouds, wind as in Series A, temperature 15°C, atmospheric pressure 1015 mb.

Series C: time 88-09-06, 05:05-05:16 LT, 16384 measurements with 0.04 s intervals (only signals from antenna 1 were recorded), fog, velocity of wind less than 0.3 m/s at a height of 2 m, temperature 10°C, atmospheric pressure 1013 mb.

VARIABILITY OF THE VERTICAL CURRENT

The vertical current consists of conduction current, displacement current, and convective current

$$j = \lambda E + \varepsilon_0 \, \mathrm{d}E/\mathrm{d}t + j_c \quad , \tag{2}$$

where λ is the conductivity of the air, and ε_0 = 8.85 pF/m. Reduced antenna signal I/S, where I is the current strength, and S is the effective area, is the estimate of the vertical current density. In the conditions under consideration the role of convective current in the antenna signals is negligible. The air ion adsorption as a convective disturbance can easily be estimated by means of semi-empirical formulas know from the heat exchange theory. For a 2-3 m high wire antenna, the respective calculation yields an adsorption disturbance of less than 10^{-3} pA/m^2.

The ratio of conduction and displacement currents depends on the time of signal smoothing. The typical value of the conduction current is about 2 pA/m^2. A 1 V/m change of electric field in 1 s corresponds to a density of the displacement current of 8.85 pA/m^2, which exceeds the conduction current. If the smoothing time is some tens of seconds or less, the variations of the displacement current are generally dominant.

The main cause of short-term variation of the electric field is horizontal inhomogeneity of the space change density of moving air. The source of vertical inhomogeneity is the electrode effect, whereas horizontal inhomogeneity arises in the mixing of vertically inhomogeneous air which takes place due to large-scale turbulence and convection. The following example enables us to estimate the variation amplitude. Let the sides of a block of air be about 100 m, the difference of space charge in neighbouring blocks 10 e/cm^3, and the wind velocity 5 m/s. This would mean a change of the electric field of about 15 V/m in 20 s, which gives a density of displacement current of about 6 pA/m^2. This is three times higher than the conduction current.

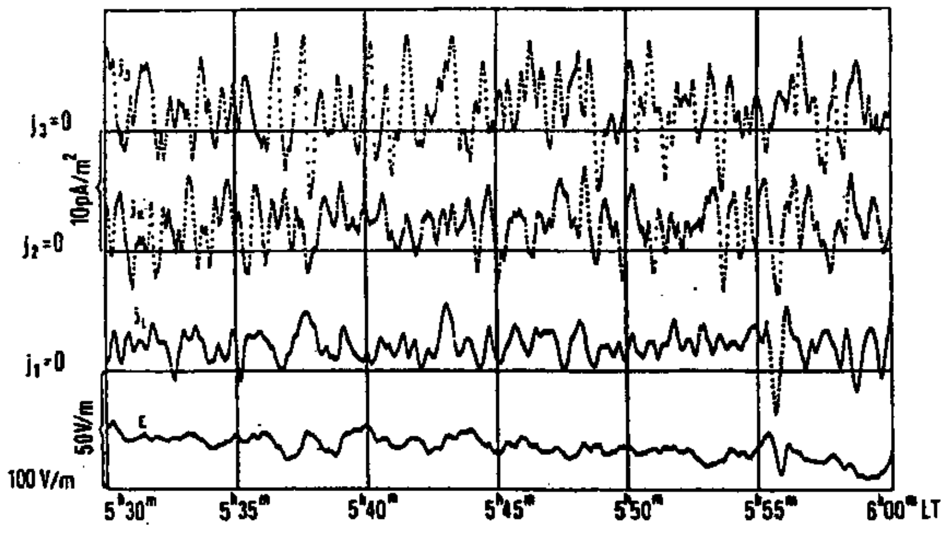

Fig. 2. The time variation of electric field and vertical currents measured by three antennas in the first half-hour of Series A. Data are smoothed by formula (1) and correspond to the time constant 10 s.

Figure 2 demonstrates the behaviour of real antenna signals in the conditions of minimum variability.

Actually the variability of signals measured with 1 s time constant was slightly higher than that depicted in Fig. 2. The dependence of standard deviation on the time constant is presented in Fig. 3.

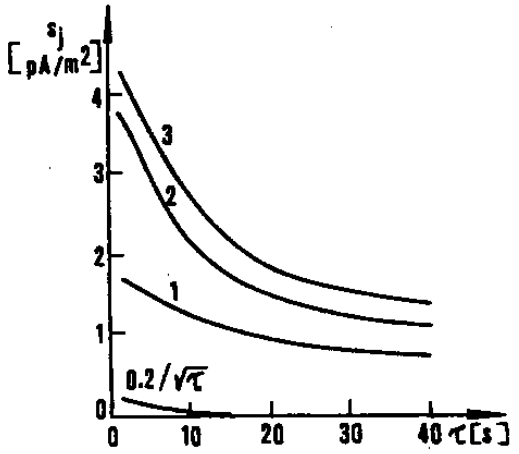

Fig. 3. The dependence of the standard deviation s_j of three antenna signals on the time constant τ of the smoothing for the first 512 s of Series A.

The low variability of the signal of antenna 1 can be explained by the fact that the antenna was shielded from the northern wind by trees (see Fig. 1).

The supplementary curve $0.2/\sqrt{T}$ in Fig. 3 presents a rough estimate of the global short noise of the ionosphere charging. Due to the continuity of Maxwellian current, the relative standard deviation of global short noise is identical everywhere. If we take the number of charging events of the ionosphere in 1 s to be 100 and assume the Poisson distribution, then we obtain 10%, as a relative standard deviation of average current density is 0.2 pA/m^2. It should be mentioned that the standard deviation of equivalent field strength 0.022 V/m would make up only 0.015% of the average field strength.

More detailed information on the character of the variations is given by the frequency spectrum of the signal. To obtain the frequency spectrum, Fourier transformation of 512-point segments of observation series was applied over all the segments. Such a method makes it possible simply and reliably to estimate also the random errors of the calculated spectrum.

Figure 4a presents the frequency spectrum of the antenna shielded from the wind. Logarithm-logarithm scale facilitates the finding of power approximations. In the range 10-100 mHz the spectral function g is approximately proportional to the frequency in power -3/2. This differs substantially from the results of Anisimov (1988). The reason can be the fact that the power -2/3 proposed by Anisimov is realized when the variations are caused by free turbulence behaving according to the theory of Kolmogorov-Obukhov. In the present case in the extremely weak wind the exchange layer is situated low and the dimensions of convection cells are small. In the frequency range below 100 mHz the main cause of the variations seems to be the convection which can be taken to account for the

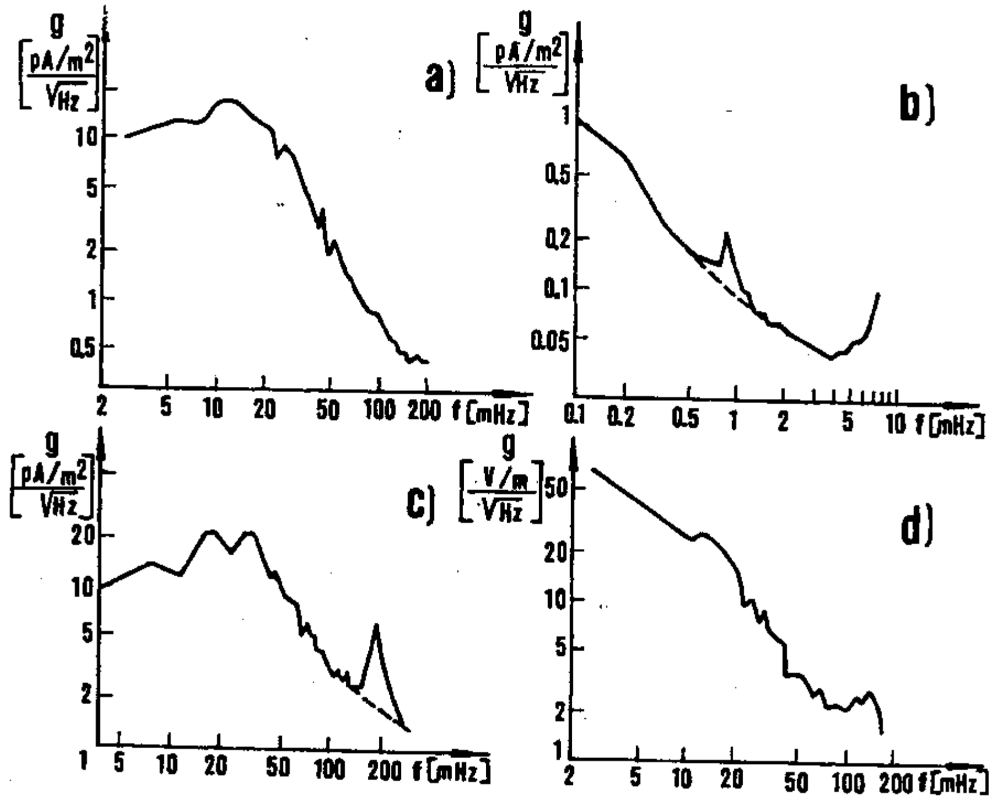

Fig. 4. The spectra of effective values (square root of the power spectrum) of current density and field strength: a) Series B, antenna 1; b) Series C, antenna 1; c) Series A, antenna 2; d) Series B, field mill.

prominence of frequencies around 10 mHz. This means random quasi-periodical oscillations in the time curve, and negative auto-correlation around half-periods. Figure 4b corresponds to the signal of the same antenna in the range of higher frequencies. In the interval 0.2-3 Hz, Anisimov's -2/3 power approximation is suitable; in this region free turbulence is evidently dominant also in the extreme conditions under observation. The neighbourhood of 0.9 Hz offers special methodological interest. The peak can be explained by mechanical vibration of the antenna. The mechanically measured resonance of antenna 1 was at 0.91 mHz. If the electric field strength is 100 V/m, then a vibration of the antenna with 1 cm amplitude causes a voltage signal up to 1 V, which would correspond to a signal of current density of 10 pA/m^2. Therefore, the mechanical vibration of the antenna is a significant source of disturbance which is necessary to be taken into account in the planning of the experiment. The dashed line in Fig. 4b implies the possibility of correction of small vibrational disturbance by interpolation.

The effects of small convection cells and mechanical vibration of the antenna are further demonstrated in Fig. 4c. Here the frequency of convection cell alternation is slightly higher due to a different meteorological situation and higher wind velocity at the location of antenna 2. The peak at 180 mHz deserves special attention. The mechanical resonance of antenna 2 was at 1.18 Hz. The frequency of 180 mHz is the result of interference with a scan frequency of 1 Hz. This shows that mechanical vibration of the antenna can cause significant disturbances of the lower frequency ranges.

Figure 4d presents the spectrum of the electrostatic field. The power -1 is better for approximation than the power -5/3 offered for normal conditions by Anisimov (1988). The spectrum contains a maximum in the region of 0.1-0.2 Hz, which cannot be accounted for by random oscillations. It is bound to have a meteorological cause, as there are no mechanical vibrations in the case of the field mill. It is possible that the frequency 0.1-0.2 Hz is characteristic of the turbulence caused be trees (see Fig. 1). The prominence of certain frequency and the corresponding quasi-periodical processes is important in understanding the following treatment of the peculiarities of correlation analysis.

THE CORRELATION OF VERTICAL CURRENTS

Figure 2 contains several events in which the correlation of d*E*/d*t*, and of j_1 and j_2 seems to be evident. For instance, at 5^h56^m LT the sharp drop of *E* induces a negative current density recorded by antennas 1 and 2. Similarly, there is a correlation in the process connected with the subsequent growth of *E*. This event is not noticeable in the signal of antenna 3. It can be supposed that at 5^h56^m LT a cloud of negative space change passed over antennas 1 and 2, and that the influence of the cloud did not extend to antenna 3. The extention of the cloud in time was about 30 s and in space about 100 m. As the influence of the cloud did not reach antenna 3, the height of the cloud could not have considerably exceeded 100 m. It is possible to attempt to correlate such a cloud with a convection cell. Though pointing to a correlation, the similarity of the curves in Fig. 2 does not serve as a rigorous proof of it. To prove the correlation, a reliable mathematical-statistical technique is required. The choice of such a technique should be guided by specific circumstances which can be explained by examples.

It is customary to identify the existence of a correlation by the estimate of the linear correlation coefficient. If we have *n* pairs of values of two fluctuating variables, whereas all the values are independent of each other, then at the repetition of series consisting of *n* pairs the estimate of the correlation coefficient would fluctuate so that in *p*% of series it would not exceed a critical limit

$$r_p = 1/\sqrt{1 + (n-2)/t_p} \ , \qquad (3)$$

where t_p is a p percent point of the Student distribution with n-2 degrees of freedom. The table of the values t_p can be found in every handbook of mathematical statistics. For high values of n, t_p can be substituted by a p percent point of the Gauss distribution, e.g., $t_{1\%} = 2.33$, $t_{0.1\%} = 3.09$, etc. If calculated according to observations $r > r_p$, then it is argued that a hypothesis of independency can be refuted at a $p\%$ significance level. The level of significance means the probability of making a wrong decision.

The above simple procedure is not useful in the case of our problem. Let us have a look at actual data in Table 1.

TABLE 1

Estimates of standard deviation s (in pA/m^2) and correlation coefficients r (in percent) of antenna signals according to the 88.09.07, 5^h30^m-6^h38^m LT observations for 512 s segments and the whole series. The subscripts at s and r are the numbers of the antennas, number 0 signifies the current density $\varepsilon_0\, dE/dt$ calculated on the basis of the signal of the field mill

Seg.	s_1	s_2	s_3	r_{01}	r_{02}	r_{03}	r_{12}	r_{13}	r_{23}
1	1.7	3.7	4.3	6	0	-1	-17	6	-8
2	1.5	2.5	4.4	2	0	0	34	1	7
3	1.6	3.6	4.2	5	-1	3	17	-6	21
4	2.3	3.4	3.8	15	-2	0	-1	-11	-4
5	2.0	3.8	4.7	10	-3	-1	6	12	-14
6	1.7	4.4	4.4	4	-3	-1	10	-14	11
7	2.0	3.1	4.3	12	-1	0	34	-17	-5
8	1.9	4.8	4.7	9	0	-2	44	-1	9
Σ	1.9	3.7	4.4	9	-1	0	16	-3	3

First of all, let us consider the fact that the fluctuation of the estimate of some correlation coefficients at the repetition of series is greater than the potential fluctuation of the correlation coefficient of independent values in the case of the above procedure. For $n = 512$ the estimate of the correlation coefficient of independent values should fluctuate so that $\rho_{10\%} = 5.7\%$ and $p_{1\%} = 10.3\%$, but the fluctuation of r_{23} at eightfold repetition of the series is from -14 to +21%.

Second, let us note that the estimate of the correlation coefficient is heavily dependent on the degree of time smoothing of the signal. This is demonstrated by Table 2. The above peculiarities are caused by the fact that the correlation between the neighbouring values of the signal of one and the same antenna is an autocorrelation. It can be said that the relation $r > r_p$ allows us to refute the independence hypothesis, but does not prove the dependence between the signal of different antennas, as the relation $r > r_p$ can be caused by the dependence or autocorrelation of neighbouring signals of one and the same antenna.

TABLE 2

Estimates of correlation coefficient r (in percent) of the signals of antennas 1 and 2, according to the 88.09.07, 5^h30^m- 6^h38^m LT observations for 512 s segments and the whole series depending on the time constant τ [in sec] of exponential smoothing

Seg.	$\tau = 1$	$\tau = 5$	$\tau = 10$	$\tau = 15$	$\tau = 20$	$\tau = 30$	$\tau = 40$
1	16	-20	-26	-32	-40	-53	-63
2	34	39	35	30	25	19	14
3	17	15	13	13	15	17	19
4	-1	5	8	6	4	0	-3
5	6	8	15	20	23	25	23
6	10	19	26	26	24	20	16
7	34	43	44	40	34	25	20
8	44	52	59	62	63	64	64
Σ	16	20	22	22	20	16	12

A characteristic example of the influence of autocorrelation on the correlation of observation series is presented in Fig. 5. Here the signals of two antennas have been correlated with 34-35 minute time shift, thus ensuring the absence of physical relation. The correlation estimate can differ from zero only by random fluctuations. The oscilla-

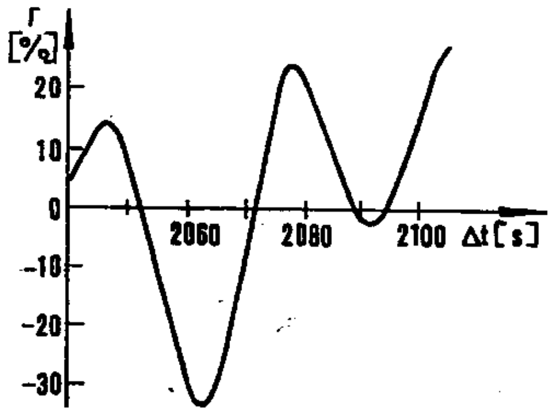

Fig. 5. The correlation between $j1(t)$ and $j2(t+\Delta T)$ for 512+512 observations from Series A.

tion of the curve $r(\Delta t)$ is typical for actual data. If we did not know its origin, there would be a danger of false conclusions. Actually, high values of the correlation coefficient and the quasi-periodical dependence on Δt are caused by an identical periodical autocorrelation (due to convection cells) in the signals of both antennas. The correlation between the signals of two antennas in Fig. 5 is dependent on how the phases of random oscillations present in the signals of both antennas coincide.

It is a rather complicated task to avoid the disinforming influence of autocorrelation. Several approaches are possible.

As an introduction we consider a hypothetical example. Let us divide an observation series of n subsequent observations into short sub-series, each containing k measurements. Let us now suppose that inside every sub-series the observation results are equal, i.e., have a 100% autocorrelation, and, further, that the results of different sub-series are independent, i.e., have a 0% autocorrelation. In this case the above technique of comparison could be applied with full rigour by substituting n in formula (3) by the number of sub-series n/k. The number k could here be called the effective scale of autocorrelation and the number n/k the effective number of independent values. The latter concepts could be fruitfully generalized, if we had a reliable technique for the determination of the effective scale of autocorrelation. Unfortunately, no such technique is available.

The standard approach to the comparison of autocorrelated time series is as follows. An autocorrelated time series is described by a mathematical model which distinguishes the dependence between neighbouring values from the cause of independent random fluctuations (see, e.g., Box and Jenkins, 1970). The simplest model is

$$x_i = a\,x_{i-1} + z_i \quad , \qquad (4)$$

where $x_1, \ldots, x_{i-1}, x_i, \ldots$ are values of an autocorrelated variable, a is a constant coefficient and $z_1, \ldots, z_i, \ldots$ are uncorrelated random variables or initial impulses. When the model is known, it can be attempted to determine the series $\{z_i\}$ proceeding from the data $\{x_i\}$. In example (4), this is relatively simple. Next, the correlation between the initial impulses of the simultaneously measured time series is calculated, with the critical limit (3) valid for the correlation. The use of the above standard technique for our problem can lead to serious errors. The reason lies in the fact that it is generally difficult to model real autocorrelation and that any model could be treatad only as an approximation. Even if the model were exact, the exact values of its parameters could not be determined. Therefore, the initial impulses which are actually calculated are not completely free of autocorrelation. As a rule, weak but large-scale autocorrelation is retained. This can significantly influence the correlation estimate. The danger of committing an error increases with increasing length of time series that are being analyzed.

THE PROOF OF CORRELATION

In the case of data with an autocorrelation the model of which is not strictly identified, the correlation can be proved by comparative methods where only the stability of correlation model is presupposed a priori. Let us consider one of these methods in application to the analysis of the actual data.

Let us divide 4096 s observation series A into 8 segments of 512 s and calculate the estimates of correlation coefficient of two antennas by segments. A causal relation between the signals can be supposed to exist only when the signal series of both antennas are taken from the same time segment. Let us now calculate the estimates of correlation coefficient for segment combinations shifted in time: here, the differences of results from zero are conditioned by chance. Actual results can be found in Table 3.

Now we shall have a look at the position of diagonal elements in the depending order of the 64 figures in Table 3. For instance, the element with a value of 44% would occupy the first position. The positions of all 8 diagonal elements are 1, 2, 4, 9, 18, 25, 32, 58 and they come before most correlation coefficients accountable for by pure chance. But would it be sufficient as a proof of a correlation manifest in the values of the diagonal elements? To answer this question, statistical tests called non-parametrical or rank tests are used. For the descriptions of the tests see, e.g., Van der Waerden (1969). For the comparison of empirical correlation coefficients, Van der Waerden's X-test is favoured; here, it would yield: **the hypothesis of independence of signals j_1 and j_2 can be refuted at the significance level 0.6%.**

A reliable refutation of the independence hypothesis is the proof of a positive correlation. Accepting the proof we risk an error with a probability of 0.6% which is the probability of random location of diagonal elements at or over the above limit.

TABLE 3

Estimates of correlation coefficients of antenna signals (in percent) for segment combinations of Series A

j_1 segment	j_2 segment							
	1	2	3	4	5	6	7	8
1	-16	6	15	8	1	-25	-2	10
2	6	34	4	-5	17	34	-19	-2
3	5	-19	17	-15	-17	-2	12	-4
4	-6	14	13	-1	-7	-9	25	-25
5	-8	14	-9	7	6	-3	-4	18
6	3	-1	6	3	-4	10	-16	25
7	9	-20	-3	20	-7	-15	34	6
8	-13	-2	13	-4	-13	-7	-15	44

The lengthening of the uniform observation series improves, and shortening deteriorates the possibilities of proving a correlation. If we used the first half of observation Series A (the first quarter in Table 4), then proving the correlation with the X-test we would get a minimum significance level of 20%.

One of the vital questions of planning the observations is how the smoothing of the signal influences the possibility to prove a correlation. It was demonstrated that, as a rule, smoothing brings on the growth of the estimates of correlation coefficients, yet this is true also of the diagonal and non-diagonal elements in Table 3. Table 4 presents the results obtained in the study of actual observation series according to the above method.

The impression suggested by Table 4 that the most suitable time constant for smoothing is 5-10 s may well turn out to be premature. The most feasible way of filtering the signals depends on the peculiarities of the frequency spectra of their common component and individual components. An important part in the common component of the signals considered in Table 4 is played by local processes; Table 4 merely demonstrates a method applicable in the preliminary analysis of the data of global experiment.

TABLE 4

The minimum significance level (in percent) of the proof of a correlation dependent on the time constant of signal smoothing. Asterisk * means that smoothing has been replaced by differentiation $x_i = x_i - x_{i-1}$, where $\{x_i\}$ is the signal which has undergone apparatus smoothing with the time constant of 1 s. The signal of antenna 0 is the variable $\varepsilon_0\, dE/dt$ calculated on the basis of the indications of the field mill. The data are constituted by Series A divided into 8 segments

Antennas	Time constant of smoothing [s]					
	*	1	5	10	20	30
0 & 1	>50	0.0003	0.0002	0.0001	0.0007	0.003
0 & 2	>50	>50	18	16	21	16
0 & 3	>50	>50	>50	>50	>50	49
1 & 2	5	0.6	0.3	0.2	2	7
1 & 3	>50	>50	>50	46	23	14
2 & 3	1	25	37	45	>50	>50

The above statistical method poses the question about the number of segments in one series. General considerations allow us to assert that shorter segments should improve the possibilities of proving a correlation. Complications will arise when the length of a segment becomes comparable to the autocorrelation scale of the signals. Therefore, the choice of too short segments is to be avoided. The considerations are confirmed by the example in Table 5. The latter question must to be studied in the stage of preliminary analysis of global experiment data.

In the case of sufficiently short segments, the above method can be viewed as a formalization of the activity of the student who, by visually comparing parallel graphs of the signal in Fig. 2, tries to find matches between events of the segment scale and to estimate the possibility of chance match for every particular type of curve.

TABLE 5
Minimum significance level of the proof of a correlation in the comparison of the signals of antennas 1 and 2 in Series A

Number of segments	4	8	16	32
Segment length [s]	1024	512	256	128
Min. signif. level	5.8%	0.60%	0.34%	0.032%

CONCLUSIONS

The considered fluctuations of the signal of vertical current antenna agree with simple theoretical estimates of the generation of local variations in convective and turbulent mixing of the electrode layer of the atmosphere.

The fluctuation of the signal is determined not by the effective area of the antenna but rather by its length. To suppress the fluctuations arising due to convection, the length of the antenna must achieve hundreds of metres; the effect depends on the relation of the scale of convection cells and the length of the antenna. Especially confusing in the identification of global effects are quasi-periodical local variations, as phase-matches can cause significant apparent correlations between the signals of two antennas. These quasi-periodical local variations may be caused by a cell-structured convection, but also by mechanical vibration of the antenna; the signals will then contain both the vibration frequency and the interference frequency of the vibration and the scanning frequency.

The vibration of an antenna with one resonance frequency is easily identificable in the frequency spectrum of the signal. In the case of several resonance frequencies, characteristic of net antennas, the identification of the effect of mechanical vibrations is more difficult.

The signals of two antennas should be compared taking into account the scanning frequencies and the time constant of signal smoothing. If the optimum mode of signal smoothing is not known, it is reasonable to use in recording a scanning frequency which is of maximum interest, and to choose a time constant of apparatus smoothing approximately equal to the scanning period.

Local variations of vertical current density would be diminished by locating the antenna above the convection layer. For this purpose, tall buildings or balloons tethered with three wires could be used. Minimum local variation of current density could be expected under the conditions of large scale temperature inversions which occur in the nighttime in continental winter anticyclones.

The decision on the correlation of the signals of two antennas must not be made on the basis of the value of calculated correlation coefficient. A sound decision can be reached through juxtaposition of segments of simultaneous and time-shifted series by comparing the estimates of calculated correlation coefficients.

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