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Recommendations for Vertical Current Measurement as Part of Simultaneous Observations of the Global Atmospheric Electric Circuit

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Abstract

Various technical problems are considered concerning the air-earth current density recording to be applied in the studies of the global atmospheric-electric circuit. On the basis of theoretical treatment and practical experience it was concluded that the effect of geometrical averaging of the measured current density depends on the greatest linear measure rather than the area over which the averaging is made. A suitable averaging range is established by means of 1-km or longer horizontal wire; the length depends on the height of the convective mixing layer. The range of averaging over time is preliminary established at one second, according to the GAEM program.

The level of the standard deviation of measured values is proposed to serve as a practical criterion for selecting the measurement periods corresponding to the fair-weather conditions. The details of the design of a long, horizontal antenna and of recording system are discussed and some recomendations are given. The recording equipment and the measurement program used by the author is described.

1. INTRODUCTION

This paper will consider technical problems of the measurement of vertical atmospheric electric current density in view of a program of simultaneous observations of the global atmospheric electric circuit. The recommendations are based on the experience of the Waldorf-Vilsandi experiment (Ruhnke et al., 1983) and the special test measurements carried out at Puise, Estonia, in summer 1988.

The measured quantity is the total Maxwellian current density, as has been proposed by Ruhnke (1969). The current density for an infinitely short interval of time and a geometrical point is not unambiguously defined and does not present any real interest. Therefore, the current density will be considered as an average over some finite area and time interval.

The range of averaging over the time is defined by the goals of the program of simultaneous observations. According to a preliminary agreement, it is one second.

Averaging over the area increases the relation of global and local variations in the data. Thus, it is reasonable to measure over a maximum technically possible area. Both the theoretical considerations and experience enable us to conclude the following:

- the effect of geometrical averaging is determined by the greatest linear measure rather than the area of the region;
- the scale of linear measure is the height of the convective mixing layer (for favourable observation conditions of global variations the height is usually 10-100 m).

A suitable averaging range is established by means of a 1-km or longer horizontal wire antenna.

The average value of the current density in medium latitudes is about 2 pA/m^2; for high latitudes, it can be several times higher.

2. THE FAIR WEATHER CRITERION

In simultaneous observations of the global atmospheric electric circuit, weather is important as far as it influences local variations. Thus, the level of local variations is the primary criterion, and meteorological data must be considered as indirect information that can be used for predicting the level of local variations of atmospheric electricity.

Experience demonstrates that the recording of vertical current density is a special situation where the direct estimation of local variability is easier and more exact than the prediction on the basis of meteorological data. The special situation is conditioned by the fact that in the local variability of the vertical current the local component usually significantly exceeds the global component and therefore the general variability can be used as an estimate of local variability.

The standard deviation of an observation series is suitable as a quantitative measure of variability. The statistical estimate of standard deviation s depends on the definition of the elements of the series and the length of the series. Our recommendations are as follows:

- the elements of an observation series are direct values of current density, recorded every second according to the technique described below;

- the estimates of standard deviation are computed for every 600-second segment of series, independently of other data.

Observations are considered to correspond to the criterion of fair weather if

$$s < s_0 \ ,$$

where s_0 is the conditional critical level. The value(s) of the critical level(s) must be determined during the actual observations. It is possible to fix several critical levels to classify the data according to their quality.

The experience enables us to suppose that the values of the critical level 0.1--1.0 pA/m^2 are likely to find application.

The above proposal defines the criterion of fair weather separately for every 10-minute interval. It is convenient to characterize long observational series by the percentage of 10-minute subintervals which correspond to the described criterion.

3. THE ANTENNA

The easiest way to obtain a 1-km linear measure necessary for geometrical averaging is a horizontal wire antenna. The antenna must be electrically insulated from ground but maintained near the zero potential. The vertical current gathered by the antenna is

$$I = S j \ ,$$

where S is the effective area of the antenna and j is the vertical current density. The effective area of the horizontal wire is

$$S = \frac{s \pi h l}{\ln(2h/r)} \ ,$$

where h is the height over ground, l is the length and r is the radius of the wire. Table 1 presents a selection of values computed according to this formula.

It is useful to hang up the wire as low as possible. This decreases the probability of corona discharge on the hair which have adhered to the wire and facilitates the cleaning of the wire and the insulators. However, at the same time the wire should be located suf-

TABLE 1

The effective area (m^2) of a 1-km horizontal antenna depending on the height and the diameter of the wire

Height	Wire diameter $2r$ [mm]				
h [m]	1	1.5	2	2.5	3
1	758	796	827	852	873
2	1398	1464	1515	1557	1593
3	2007	2097	2167	2224	2273
4	2596	2710	2797	2868	2929
5	3172	3308	3411	3496	3568

ficiently high in order not to hinder the movement of people and animals. Elks can harm antennas at heights up 2.5 m. For higher antennas it is easier to take into account the topography.

On the basis of experience, the height of 2-3 m and the diameter of 1.5-2.5 mm can be recommended. A finer wire is a lighter mechanical load on the insulators. The possibility of corona discharge on the surface of the wire does not deserve attention. In practice, corona discharges arise independently of the wire diameter on the hair gathered on the wire and never on the wire itself.

Corona discharges on long spider threads stuck to the wire start already when the product of the field strength and the height of the wire achieves 500 V. The current strength of such a discharge is comparable to the strength of the vertical current and thus it is difficult to identify it on the basis of the antenna signal. This causes considerable complications in the period of the activity of flying spiders.

The electric properties of the antenna are independent of the material of the wire as the resistance can be considered sufficiently low, even at 1 MΩ.

Technically suitable materials are alloyed aluminium and zink-plated steel. The diameters recommend for aluminium and steel are 2-2.5 and 1.5-2 mm, respectively.

4. SUPPORTING AND TIGHTENING OF THE WIRE

A technically suitable tightening force for the wire is near to the conditional standard tension. The conditional standard tension for a 2-mm aluminium wire is 11 kG and for a 1.5 mm steel wire it is about 18 kG.

The sag of a wire of conditional standard tension is about $(l : \mathrm{m})^2/100$ cm , where l is the distance between supports. Examples:

wire length	30	40	50	60	70	m
sag	9	16	25	36	49	cm

The sag criterion makes it possible to locate the supports at a distance up to 60 m from one another. However, such a long distance is not recommended in view of other factors. There are cases when the topography makes it necessary to locate the supports closer to one another.

The most sophisticated factor at the choice of supports and tension is the mechanical vibration of the wire. When a 2-mm wire at a height of 2.5 m vibrates in an electric field of 100 V/m with a frequency of 1 Hz and an amplitude of 1 mm, it causes an induced current with an amplitude corresponding to a current density of 3.6 pA/m^2. This example demonstrates the extent of the disturbances caused by the vibration of the wire.

Disturbances caused by vibration in the neighbourhood of 1 Hz or its multiples are especially unpleasant. Scanning the signal with a frequency of 1 Hz, we turn out to be in closely spaced phases of the disturbance signal in successive seconds. As a result, we get beats of very low frequency.

The eigenfrequency of a string with rigidly fixed ends is

$$f = \frac{56\mathrm{m}}{l}\sqrt{\frac{F}{F_o}}\ \mathrm{Hz}\ ,$$

where F is the actual tension of the string and F_o is the standard tension. When the fixation is not quite rigid, the corresponding frequency will be lower.

While locating the supports for the antenna it is extremely important to take into account the eigenfrequencies of the wire. For $F = F_0$ the distances in the neighbourhood of 56 and 23 m are most unfavourable. To obtain a more suitable eigenfrequency of 1.5 Hz, the distance between the supports should be 37 m. The eigenfrequencies can be adjusted later by changing the tension of the wire.

The fixation of the wire should hinder the vibration. If the wire is tightened using a spring or a weight hung over a pulley, a damper adjusted to the critical regime must be used.

5. THE INSULATORS

When a compensating operational amplifier is used, the passive leak current of the insulators can be neglected and the criterion of insulation is the active current caused by the electro-chemical electromotive force which can reach a value up to 1 V. For a 1-km antenna the spurious currents lower than 0.1 nA can be neglected and the limit of noticeable disturbance is about 1 nA. It follows that the critical value of total resistance of the insulators is about 1-10 gigaohm. For all popular insulation materials the resistance caused by the spatial conductivity does not fall below one teraohm. Therefore, it is important to consider only the surface resistivity of the insulators, which depends on hydrophobic qualities of the surface. From the viewpoint of hydrophobic qualities of a clean surface, teflon is a suitable material.

The resistance of insulators can be drastically decreased by the pollution on their surface. Here the most disturbing factors are the hydrophilic traces and threads of insects and spiders. It is extremely complicated to protect the insulators from insects and therefore it is normally not attempted, thus it is recommended to use as open insulators as possible because they are easier to clean. There is no need to protect the insulators from rain because measurement results for rainy weather cannot be used anyway.

A recommendable design for the insulators is presented in Fig. 1. The insulators are made of teflon. The side surface of the insulator cylinder should be polished by turning on a lathe with a specially sharpened cutting edge. The diameter and the length of both the support and pulling insulator are about 15 mm and 10 cm, respectively. Supports with significant side forces should be avoided in the stage of the antenna disposition. This kind of insulators can be cleaned by a person standing on the ground and using a brush with a stick of 1.5 m or longer. A similar long brush is needed for cleaning the wire of spider webs and hair.

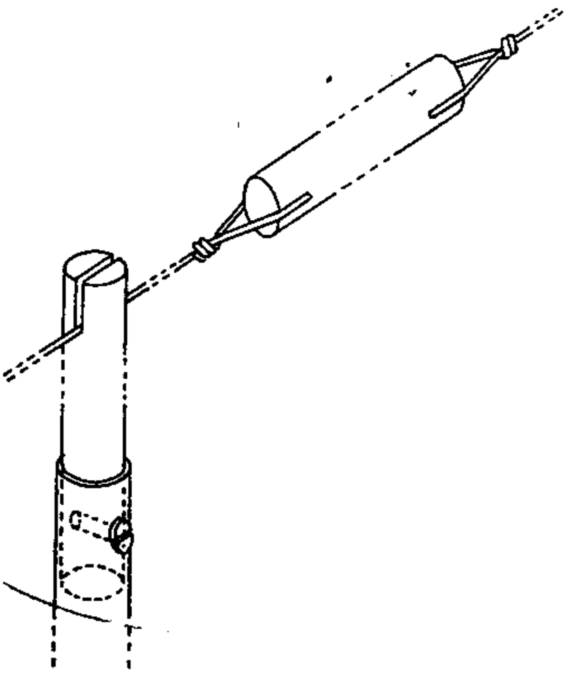

Fig. 1. Design of the insulators.

6. THE MEASUREMENT RANGE AND THE DIGITIZATION STEP

The measurement range should be sufficiently wide to avoid analog overflow (exit of the signal from the measurement range) in fair weather conditions.

The step of digitization of the signal should be smaller than the signal changes due to local reasons and disturbances. For the sake of technical convenience, the measurement range should contain the minimum number of steps. Experience shows that the step 0.01 pA/m^2 is small enough and 0.02 pA/m^2 is also satisfactory. The digitization step should certainly not be set higher than 0.05 pA/m^2. The minimum acceptable measurement range at medium latitudes is from -5 to +10 pA/m^2. This range contains 300 maximum permissible steps of digitization, which makes it impossible to use a 8-bit analog-digital converter (ADC). The number of bits below 10 cannot be recommended. For a 10-bit ADC the step can be 0.02 pA/m^2 and the measurement range from -7.5 to +12.5 pA/m^2 or from -10 to +10 pA/m^2 in the case of a simplified equipment. In the case of an antenna with an effective area of 2000 m^2 a current strength of 40 pA corresponds to the above step and 20 nA to the above range.

7. THE AMPLIFIER AND ANALOG TRANSFORMATION

Every good integrated operation amplifier with an input current below 100 pA can be used as the amplification unit. It is necessary to use a connection which compensates the antenna current as shown in Fig. 2. The resistance of the measurement resistor should be

$$R = U_0 / (j_{\max} S) \quad ,$$

where U_0 is the ADC measurement range, $j_{\max}$ is the range of the vertical current density and S is the effective area of the antenna. Capacitor C is necessary for the realization of the suitable integral transformation. The output signal of the described amplifier is an image of physical current density exponentially smoothed in time:

$$j_\tau(t) = \frac{1}{\tau} \int_{-\infty}^{t} j(t') \exp\left(-\frac{t-t'}{\tau}\right) dt'$$

where the time constant $\tau = RC$.

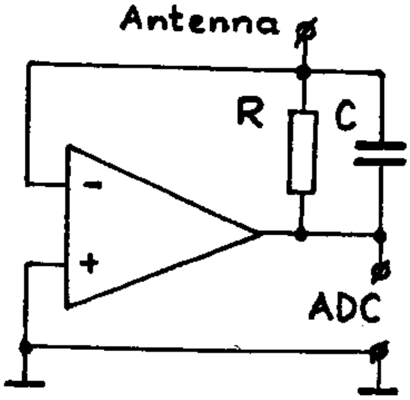

Fig. 2. Technique of compensating the antenna current.

It was mentioned in the introduction that the integral transformation cannot be avoided. In principle the transformation may be different from exponential smoothing. For instance, uniform averaging can also be conveniently interpreted

$$j_{\Delta}(t) = \frac{1}{\Delta} \int_{t-\Delta}^{t} j(t')\, dt' \ ,$$

where Δ is the time increment of the measurement (1 s according to preliminary agreement). Uniform averaging can also be realized by the use of an operational amplifier. In order to do so, resistor R in Fig. 2 should be replaced by a controlled switch, which shorts capacitor C for some milliseconds at the beginning of every second and is open for the rest of the time. In this case the output signal cannot be recorded at an arbitrary moment but just before each shorting of the capacitor.

The method of uniform averaging is not popular in practice. Therefore, we prefer exponential smoothing. The following special convention is recommended:

$$\tau = \text{signal scanning period} \ .$$

If the signal scanning period is 1 s, we should choose $C = 1\text{s}/R$.

When there is a long transmission line between the amplifier and the ADC, a high frequency noise may be added to the signal in the line. In this case it is necessary to switch a supplementary analog filter directly to the input of the ADC. The filter carries out an additional smoothing of the signal. This additional transformation should be negligibly small in comparison with the main transformation and thus the following rule should be satisfied: **the 63% transition time of the voltage jump through supplementary filter should not exceed 1/3 of the time constant of the main exponential smoothing of the signal (it is recommended not to exceed 1/5).**

If the secondary filter contains a first order RC circuit with the time constant τ_s, the rule is equivalent to the requirement $\tau_s < \tau / 3$. As more complicated (and more

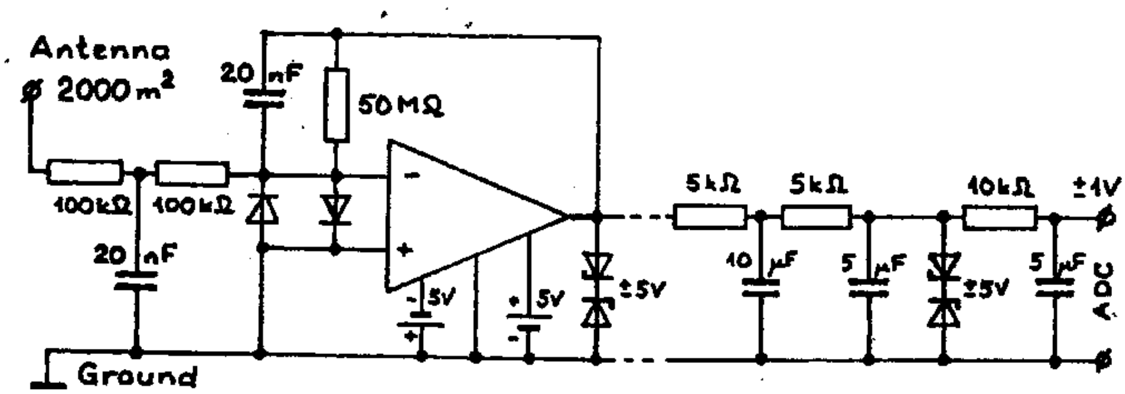

Fig. 3. Diagram of the amplifier.

effective) filters are often used in practice, the rule has been given the above general form.

The real amplifier should contain additional components for protection against possible overvoltages. A more realistic circuit of the amplifier is presented in Fig. 3.

8. THE RECORDING EQUIPMENT

The source of the measurement process is the antenna signal, the final result is a data file on a 5 1/4 inch diskette. Figure 4 presents two variants of the equipment for this process. In the first variant, one and the same computer is used for measurement and data analysis; in the second variant, two different computers are used.

A comparative analysis shows that for one or two observation points the variants are nearly equal, while for a network of observation points with a common data center the second variant is more economical.

At least an IBM PC XT-class computer with a hard disk is needed for the data analysis. The standard desktop IBM PC power consumption is about 100 W and this makes the reserve battery power source (which is highly recommended for observation points) too big and expensive. Expenses on the reserve power source can be reduced by replacing the desktop computer by a laptop one. Laptop computers, however, are much more expensive than the standard ones.

In the case of the second variant (Fig. 4), a cheap 8-bit computer fed with a 5V 1A DC power source can be used at the observation point. A diagram of observation point equipment for the second variant is presented in Fig. 5. Special features of the computer used (ATARI 130 XE) are its minimum price, high reliability, precise built-in timer and low DC power consumption. The computer allows an easy data exchange with the ADC, and the cassette recorder ATARI XC 12 later allows an easy transmission of data to the IBM PC computer.

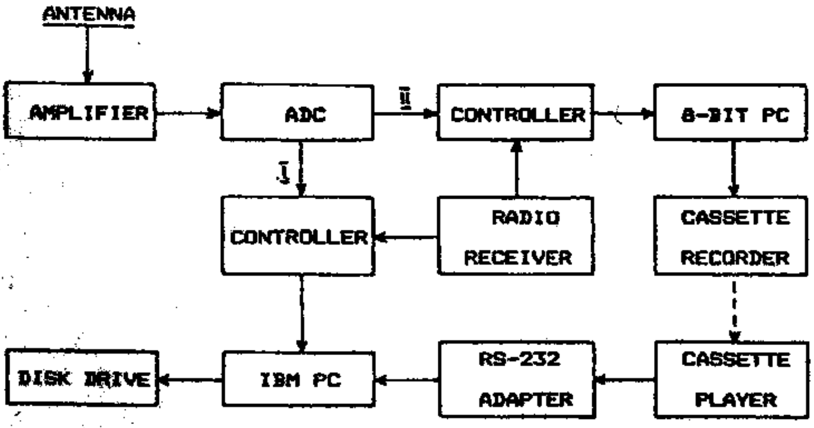

Fig. 4. Diagram of the equipment (variants I and II).

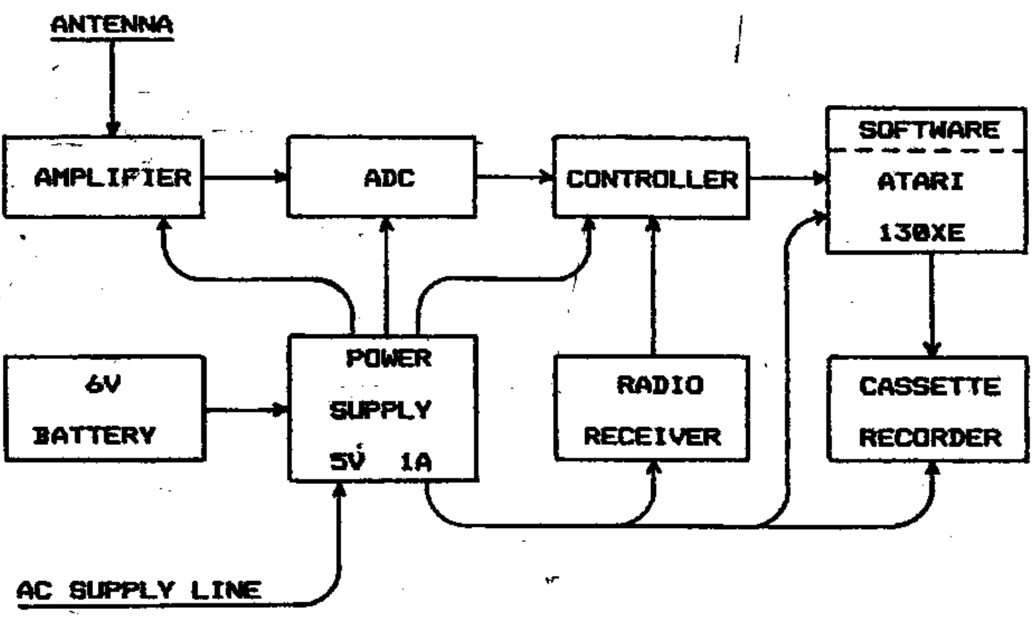

Fig. 5. Diagram of the recording equipment based on a 8-bit ATARI computer.

The radio receiver in Fig. 5 is used for the input of exact time signals to the computer. This is necessary for a precise starting of the measurement series and for the subsequent check-ups of the computer's timer. Hourly broadcasted time signals can be used and transmitted to the computer through a microphone and the controller.

In the mode of uninterrupted measurement, ATARI 130 XE allows to keep results in RAM so that at any moment the data of the last 24 hours are available. Arbitrary segment of these data can be stored on a compact cassette.

ATARI 130 XE together with ATARI XC 12 cassette recorder costs about 200 US dollars. The supplementary equipment (amplifier, ADC, controller and adapter for data transmission to IBM PC) have to be specially made. Expenses on the software should be added. A rough estimate sets the total cost of hardware and software for a network of 20-30 observation points at about 2000-3000 US dollars per point.

9. THE MEASUREMENT PROGRAM

The measurement process is controlled by a computer with the measurement program. A specific program can be written when the equipment and its parameters are fixed. The example below demonstrates the main elements of an algorithm of a simple measurement program. This example is written in a nonformal language and does not comprise all details needed in a real computer program.

Four variables are determined by external devices:

TIMER - integer variable, automatically increased by one after a certain time interval, e.g. 1 ms;

ADC - arithmetic variable with a value determined by the ADC connected to the antenna through the amplifier;

RADIOBEEP - Boolean variable; its value is TRUE only when the radio transmits the beep of exact time;

SAVEKEY - Boolean variable, the value TRUE can be given by pressing a specific key.

The variable TIMEDATE is a compound of six integer components: year, month, day, hour, minute, second.

Two specific constants are determined by the environment:

FULLSECOND - the increment of TIMER in one second,

BEEPNUMBER - the number of hourly timebeeps.

A specific variable TIMERCONTROL should make it possible to adjust the speed of the timer. If the speed cannot be adjusted physically, then the adjustment should be simulated by the program. For instance, the constant FULLSECOND can be replaced by an oscillating variable with a minimum amplitude and the structure of oscillation depending on the value of TIMERCONTROL.

The constant INITIALTIMERCONTROL should be given so that the timer error would be below some seconds per day.

The algorithm allows to start the measurement only at hourly radio timebeeps. It has been presumed that the timebeeps are transmitted at least every three hours.

The algorithm is as follows.

```
RUN:
    clear screen and display short instruction;
    read from keyboard year, month, day, hour and set TIMEDATE to the starting
    point of measurement;
    COUNTER = 0; CORRECTION = 0; EXCEPTION = 0; POINTER = 0;
    SAVEKEY = FALSE; TIMERCONTROL = INITIALTIMERCONTROL;
    wait until RADIOBEEP;
    TIMER = 0; wait until TIMER (BEEPNUMBER - 1.5)* FULLSECOND;
    TIMER = 0; wait until RADIOBEEP or TIMER = FULLSECOND;
    if no RADIOBEEP then go to ERROR;
    TIMER = 0;
```

```
MEASURE:
    wait until TIMER > = FULLSECOND;
    TIMER = 0;  increase TIMEDATE (+ 1 SECOND);
    BUFFER [POINTER] = ADC;  POINTER = POINTER + 1;
    if POINTER > BUFFERSIZE then POINTER = 0;
    display ADC and TIMEDATE;
    COUNTER = COUNTER + 1;
    if COUNTER = 3599 then
        {wait until RADIOBEEP or TIMER = FULLSECOND - 1;
        if RADIOBEEP then CORRECTION = FULLSECOND - TIMER}
    if COUNTER = 3600 then
        {wait until no RADIOBEEP;
        wait until RADIOBEEP or TIMER = FULLSECOND - 1;
        if RADIOBEEP then CORRECTION = TIMER}
    if COUNTER = 3601 then
        {if abs (CORRECTION)  FULLSECOND/2 then go to ERROR;
        if CORRECTION = 0 then
        {display "no radiobeep !";
        EXCEPTION = EXCEPTION + 1;
        if EXCEPTION = 3 then go to ERROR}
        if CORRECTION  0 then EXCEPTION = 0;
        if CORRECTION  0 and CORRECTION  MINIMUMCORRECTION
        then CORRECTION = 0;
        TIMER = TIMER + CORRECTION;
        TIMERCONTROL = TIMERCONTROL +
        TIMERCONTROL * CORRECTION / (3600 * (EXCEPTION + 1) *
            * FULLSECOND);
        COUNTER = 1; CORRECTION = 0}
    if no SAVEKEY then go to MEASURE;

SAVE:
    display TIMEDATE-range of BUFFER;
    read from keyboard TIMEDATE-range of record;
    read from keyboard the text for READ-ME file;
    save the READ-ME file to cassette or disk;
    save the heading of the record and data from BUFFER to cassette or disk;
```

```
    go to RUN;

ERROR:
    display error message;
    wait until a key on keyboard is pressed;
    go to RUN.
```

10. THE DATA STRUCTURE

The logical structure of the original observation data should be independent of the computer and data carrier. The standard structure is used for the long term storage and exchange of data. Data analysis is started on the standard structure, but during the analysis arbitrary alternative structures can be formed.

According to the following standard only one uninterrupted observation series for one antenna is written into one file. The antennas are coded numerically 0, 1, ... and the uninterrupted observation series for certain antenna are also numbered 1, 2, ...The upper limit for both the antenna number and series number is 255.

A standard data set consists of two files. The first is of a READ-ME type and contains 800 bytes of ASCII text without any EOL-byte. The text should be written so that it would be readable without any transformation both on 40 and 80-column screen, forming 20 or 10 lines, respectively. The text should contain a short description of observation conditions.

The second file contains a 10-byte heading and directly after the heading $2n$ bytes of values presenting the measurement results where n is the number of seconds of the observation series.

The measurement unit of current density in the standard data is 1 pA/m^2. The values of current density are coded in two neighbouring bytes as binary integers according to the IBM PC standard. This coding standard should be strictly followed, independently of the programming system and the computer used.

The range of the integers coded in the above way is from -32768 to +32767, thus the range of current density is from -32 to +32 pA/m^2. The overflows of the ADC or the amplifier should be coded as the lowest or highest possible integers, independently of the measurement range that is being used.

The 10-byte heading consists of ten one-byte unsigned integers (0...255) as follows:

1) number of the antenna,

2) number of the observation series,
3) value of the ADC digitization step in the units pA/m^2,
4) reserved byte (standard value is zero),
5) year-1900,
6) month (1...12),
7) day (1...31),
8) hour (0...23),
9) minute (0...59),
10) second (0...59).

The six last numbers correspond to the time of starting the measurement series (the first reading corresponds to the time 1 s later).

Bytes 11 & 12 contain the value of the current density of the first second, 13 & 14 of the second second, etc.

For writing on the diskette the files are given the names

JREAD#.@,
JDATA #.@,

where # stands for the number of the observation series and @ stands for the antenna number. Thus a 800-byte READ-ME-type file for antenna no. 12 and observation series no. 7 is named

JREAD 7.12.

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