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## PAPERS ON THE MEASUREMENT OF GRAVITY WITH USSR PENDULUM EQUIPMENT

by

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Translated from the Russian by

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## Preface

The papers translated here are extracted from "Trudy Tsentral'nogo Nauchno-Issledovatel'skogo Instituta Geodesii, Aeros'emki i Kartografii, Vypusk 170, Issledovaniya po Gravimetrii" (Transactions of the Central Scientific Research Institute of Geodesy, Aerosurvey, and Cartography, Vol. 170, Investigations in Gravimetry). They describe development work on the Russian OVM pendulum equipment which was used in Sydney in December 1972.

Copies of this volume were donated by Dr Yuri Slivin, the leader of the Russian pendulum party and author of the papers translated.

The volume contains 8 papers altogether. The first five are related to gravity measurements at sea, mainly using pendulum apparatus; these have not been translated. The sixth and seventh have been translated in full, but only the summary has been translated for the final paper as it seems to be of a rather specialized nature and of limited interest.

In the Russian volume a common bibliography was used for all 8 papers. The original numbering from this list has been used, but only those works relevant to the papers translated have been listed in the bibliography here.

It is with deep regret that we heard of Dr Slivin's untimely death in April 1973, shortly after the successful conclusion of the pendulum tie from Moscow to Sydney.

CONTENTS

# Some problems of the accuracy of photo-electric recording of periods and amplitudes of the vibrations of pendulums

Yu. A. Slivin

(Translation by J.C. Dooley)

## Summary

The prototype of a photo-electric recorder of the oscillations of pendulums is described, and problems of the accuracy of determination of the periods and amplitudes of pendulums are examined.

Principal attention is given to analysis of the operation of the pulse shaping block, the chief development affecting the accuracy of the measurement.

A method was developed for determination of the optimal operating conditions of the passive multivibrator and for evaluation of the stability of operation of the shaping block as a whole with the use of a cathode-ray tube. The following mean square errors were obtained:

(a) Instability of rotation of the rotor of the synchronous motor - 5-7 μs

(b) Tying the starting impulse to the input pulse - ± 10 μs

It was shown that 15 minutes was sufficient for measurement of the period of vibration of the pendulums with an accuracy of ± $10^{-8}$s.

The correction for asymmetry is examined in detail.

The accuracy of the measurement of amplitude by the photo-electric method is evaluated.

Future possibility of improvement in the method of photo-electric recording with the aid of an averaging device is indicated.

## General Remarks

Photo-electric recording of periods and amplitudes of oscillations of pendulums has been very widely applied recently, gradually replacing photographic recording.

In the present paper the experimental prototype of a photo-electric recorder of the pendulum oscillations is briefly described, as developed in the gravimetric laboratory TsNIIGAiK (27)-(30), and some problems of the accuracy of determination of the periods and amplitudes with the aid of this apparatus are discussed.

A photo-electric recorder, constructed on the principle of the model described earlier (30), is characterized by the following basic features.

A light impulse from the pendulums is converted by a photo-electric multiplier (FEU) into an electrical impulse of duration 1-2 ms. Then from this is formed a short starting impulse (duration 10-15 s), tied in phase with the middle of the bell-shaped impulse obtained from the anode load of the FEU. The impulse formed in this way starts and stops two counting devices. One of these counts vibrations from a quartz oscillator with frequency 100 kHz, and the other determines the number of passages of the pendulum through the position of equilibrium. The gravimetric period of oscillation of the pendulum is obtained as the quotient on dividing the indication of the first of these counting devices by the indication of the second. In this recorder the binary system of counting impulses was used because it is the most reliable. For checking the operation of the counting devices the first six binary digits were duplicated.

In high-accuracy pendulum determinations (31) the amplitude of the two actual and the fictitious pendulums are measured only at the beginning and end of a series of observations. Therefore for determination of the period and amplitude one and the same counting device was used with appropriate switching.

The prototype photo-electric recorder is illustrated in Figs. 1 and 2. On the front panel are located the indicators for the counters, the signal lamps, switches for the method of operation, circuit breakers, and lowering control buttons. All blocks of the recorder excluding the power supply can be readily detached and in case of necessity replaced by the following spare blocks:

(1) Impulse shaping block

(2) Counting device for counting vibrations of the quartz generator, consisting of electronic valves (one block) and cold thyratrons MTX-90 (second block)

(3) Counting device for counting oscillations of the pendulums consisting of MTX-90

(4) Thermostatically controlled quartz resonator, which travels separately from the recorder during transport.

In analysis of the accuracy of the operation of the photo-electric recorder (Fig. 3), principal attention is given to the operation of the shaping block. The following problems are discussed:

1. Determination of the stability of tying the starting impulse to the bell-shaped (input) impulse.

2. Influence of the parameters of the passive multivibrator $L_3$ on the measurement of the period of oscillation of the pendulum.

3. Stability of operation of the shaping block as a whole.

## I. Errors introduced by the passive multivibrator and the differentiating circuit

An impulse of negative charge and duration of 1.5-2 ms and amplitude about 0.5V is amplified by the triode $L_1$ (Fig. 3) and after truncation from below enters the differentiating circuit $C_3R_8$. The resulting signal after amplification is fed to the input of the passive multivibrator $L_3$, which trips only when a positive signal is supplied to the grid of this valve.

The leading edge of the starting impulse, obtained through further shaping, corresponds to the leading edge of the rectangular impulse taken off the anode of the passive multivibrator. Therefore the starting impulse is tied to the centre of the input impulse only if the differentiation is carried out precisely (circuit $C_3R_8$) and the passive multivibrator trips on a small voltage. For determination of the threshold of tripping a cathode ray tube is used. The impulse from the second anode of $L_1$ is fed to one pair of deflecting plates, and the starting impulse to the second, corresponding to the leading edge of the rectangular impulse from the anode of the passive multivibrator $L_3$. The threshold of tripping can be regulated from 0 to 3 volts.

It has been determined that the passive multivibrator operates reliably with a signal of 0.1 to 0.2V.

Further it should be noted that if the threshold of tripping of the multivibrator is set at 0.1V the system becomes sensitive to line interference. Therefore it is expedient to choose a certain optimal condition for the multivibrator for which the influence of extraneous noise is minimal but the magnitude of the threshold is not large (0.3 to 0.5V).

Inasmuch as the duration of the leading edge of the impulse being supplied to the passive multivibrator is 100-150 s, and its amplitude at the grid is 5-10V, then the starting impulse may shift relatively to the centre of the bell-shaped impulse by as much as 20 μs.

A much larger delay of the starting impulse occurs with inappropriate choice of parameters of the differentiating circuit. It is enough to say that an increase of the capacity of $C_3$ from 51 to 430 pF causes a delay of the order of 500 μs.

II. Investigation of the stability in time of tying the starting impulse to the bell-shaped impulse from the photo-electric multiplier

The initial phase of tying the starting impulse to the input bell-shaped impulse depends on the parameters of the differentiating circuit (in particular, on the capacity of $C_3$). In an ideal operating system the initial phase does not change if the duration of the impulse from the pendulum does not change; however, owing to damping there occurs a smooth change of phase.

For investigation of the magnitude of these errors a rectangular pulse was formed from the input bell-shaped impulse with the aid of a trigger from the cathode connexion. The leading edge of the latter corresponded with the leading edge of the input impulse limited at a certain level (Fig. 4) and the rear end of the impulse with the trigger corresponding to the rear edge of the bell-shaped impulse.

From the results of the investigation the quantity:

$$\Delta = (t_1 - t_2)/2$$

was determined, where $t_1$ = interval of time between the leading edge of the rectangular and starting impulses, and $t_2$ is the interval of time between the starting impulse and the rear edge of the rectangular pulse.

A photo-electric recorder (see Fig. 3) with addition of certain commutating circuits, and the vacuum pendulum apparatus TsNIIGAiK (OVM), were used for the investigation. Observations of the fictitious pendulum formed from the two actual pendulums swinging with equal amplitudes and opposite phases, were carried out at atmospheric pressure. The intervals $t_1$ and $t_2$ were measured over each five minutes of an extended time. The experiments described were carried out under various conditions of tripping the passive multivibrator and for two values of the differentiating capacity $C_3$ (430 and 51 pF).

From Figs. 5 and 6 it follows that if the threshold of tripping of the passive multivibrator is set correctly, then for a duration of 25 to 30 minutes continuous observations the systematic error in the period of oscillation of the pendulum does not exceed $2 \times 10^{-8}$ s (curve II). In evacuated pendulum equipment the damping is diminished by a factor of approximately 5; therefore the error in counting due to an increase in the duration of the impulse is negligible.

III. Stability of operation of the shaping block

The operation of the shaping block may be checked with the aid of a generator of a stable impulse with frequency 0.5 Hz. As the laboratory was not equipped with such a generator, then for investigation of the overall error introduced by the shaping block and the instability of the power supply voltage of the FEU and the illuminating lamp, a device, the scheme of which is illustrated in Fig. 7, was used. A synchronous motor, model of the Central Scientific Investigation Institute for Physico-technical and Radio-technical Measurements (TsNIIFTRI) served as controller of the impulse. By using objectives with various focal lengths and changing correspondingly the transmitting and receiving diaphragms, it is possible to obtain impulses of various durations (from 1 $\mu$s to 2 ms and more). A cathode-ray tube with central radially deflecting electrodes (1) was used for recording.

For determination of the stability of the speed of the rotor of the synchronous motor it was necessary to exclude (or keep to a minimum) errors in the shaping of the impulse. With this objective, with the aid of the device described (Fig. 7), an impulse of duration about 1 μs was obtained. If the speed of the rotor is guaranteed with $10^{-6}$s, then the impulse through each 0.1 s appears at one and the same place of the curved section. Experiments have shown that the maximum value of instability of speed of the rotor lies within the limits 5-7 μs.

Consequently, it is possible to determine the total error introduced by the shaping block and instability of the power supply voltage to the photo-multiplier and illuminating lamp. For this the impulse obtained with the help of the arrangement described above had a duration of about 1.5-2 ms, i.e. a duration similar to that obtained from the pendulums. This impulse from the shaping cascade was fed to the cathode ray tube (ELT) with the radially deflecting electrode. The maximum scatter of the impulses observed on the screen of the ELT obtained in this way was not more than 25 μs (mean-square error ± 12 μs). The final error was actually somewhat increased, because with the experiment carried out the ELT and illuminating lamp power supply was not stabilized. Further, there was introduced also an error depending on the variation in the speed of the rotor of the synchronous motor, + 7 μs. Thus, the mean-square error in tying the starting impulse to the input pulse will be not more than ± 10 μs, while the error in determination of the interval of time is ± 14 μs. We see how the magnitude obtained for the determination of the time interval conforms with the analogous error in the measurement of the period of oscillation of the pendulum.

For determination of the accuracy of recording of the period of oscillation of the fictitious pendulum, derived from the two actual pendulums swinging with the same amplitude and phase difference close to 180°, the OVM apparatus and the photo-electric recorder described above were used. The results of the measurements of the period of the pendulum are presented in Table 1 as the time of one complete oscillation. The mean-square error of one measurement is indicated as ±11.5 μs. It is natural to suppose that the period of oscillation of the pendulum could be determined with an accuracy of $\pm 1.10^{-8}$ in approximately 15 min (about 1000 oscillations). However, in practice this is not observed. In each interval six series of measurements were determined, during which the pendulums were not arrested between separate series. The accuracy of the recording can be evaluated from the internal consistency, comparing the data for the separate series for one interval (along the rows in the table presented). Significant discrepancies in the magnitudes of the errors for one series demonstrated, obviously, that disturbing factors acted diversely on the period of the pendulum and did not remain constant over the extent of a day. This evaluation showed that in all cases the error of a single series (about 17 min) is significantly larger than calculated (26). This proves that some disturbing factors not taken into account act on the pendulums (microseisms, vibrations, frictional forces, and others). It is impossible to reveal and investigate these factors without apparatus such as photo-electric recorders, the accuracy of which, as seen above, must be substantially improved in the future.

## IV. Corrections for asymmetry

In determination of the period of oscillation of the pendulum by the method of photo-electric recording, the impulse from the FEU must always be fed in at that moment at which the phase of the pendulum is the the same. In order to maintain this condition it is essential that the image of the transmitting diaphragm reflected from the mirror on the pendulum is projected onto the slit of the receiving diaphragm at the moment when the pendulum passes through its position of equilibrium.

If the pendulum was not damped, then it would make no difference which phase corresponds to the starting impulse. With damping of the oscillations the phase of the pendulum at the end of a series of observations will not be equal to the phase at the beginning. Therefore in measuring the period of oscillation of the pendulum it is necessary to introduce a correction which in the following we will call the correction for asymmetry (for asymmetrical disposition of the points corresponding to the range of motion of the pendulum relative to the receiving diaphragm).

If at the time of observation the position of the receiving diaphragm is not changed, then depending on the direction of motion of the pendulum it is possible to determine with the help of the photo-electric recorder the magnitude (see Fig. 8):

$$S_1 = t/N \quad \text{or} \quad S_2 = t'/N$$

where N is the number of oscillations of the pendulum and t and t' are the times determined by the counting device.

In the case shown, $S_1$ will be less and $S_2$ larger than the value of the period by approximately the same amount. Let the phase of the pendulum at points b" and c" be the same as the phase at points b and c (at the beginning of the series). Further let us achieve measurements of the intervals of time $t_1$ and $t_1'$. Then $S_1'$ and $S_2'$ and $S_2' = t_1'/N$ are the true values of the period.

From Fig. 8 it is easy to determine that the asymmetry ($S_t$) expressed as a time will be

$$\delta_t = (t_{dom} - t_{do'n})/4$$

where $t_{dom}$ = larger observation of the half-period of oscillation of the pendulum

$t_{do'n}$ = smaller observation of the half-period.

Now the asymmetry in units of length is

$$\delta_1 = a \sin(\pi/S)\ \delta_t$$

where a is the amplitude of oscillation of the pendulum and S is the half-period.

If at the beginning of a series of observations the asymmetry was equal to $S_{t1}$, and at the end $S_{t2}$, then the correction for asymmetry $\Delta S_\delta$ is obtained as

$$\Delta S_\delta = (\delta_{t2} - \delta_{t1})/N$$

Thus, the correction for asymmmetry $\Delta S_{\delta}$ is determined with the aid of a photo-electric recorder, if two consecutive (large and small) half-periods of vibration of the pendulum are measured at the beginning and end of a series of observations.

As an illustration we point out that asymmetry of $\delta_{\ell}$ equal to 0.1 mm (f = 540 mm) causes an error in the period of oscillation of the pendulum of $\pm$ 4 x $10^{-8}$ sec with an initial amplitude of 40'.

The correction for asymmetry is larger for a larger coefficient of damping, which depends on the circumstances of the observations (in a vacuum or in the atmosphere), the shape of the pendulum, and the material of the supporting fixtures (knife and flat).

For determination of the asymmetry $S_t$ with the photo-electric recorder, the leads (1, ya) of the relay $R_2$ must be disconnected (see Fig. 3). In this case the system will operate as follows.

The first impulse from the photo-multiplier will trip the auxiliary trigger $L_4$, and after a certain delay the relay $R_1$, one of the windings of which is located in the anode circuit of $L_4$. A positive charge is taken off by this from the left half of $L_5$ and the second impulse from the photo-multiplier passes through to the network 2 of the principal trigger $L_6$, starting the counting device. As only the first valve MTX-90 is opened, the circuit 1, ya is broken by the relay $R_3$ in the device for counting oscillations of the pendulum, and the impulse will no longer be admitted to grid 2. The third impulse, passing through the right half of $L_5$ to grid 7 of the principal trigger, brings it into the original state and the counting device stops counting. The impulse admitted to grid 7 of $L_6$ during each half-second cannot change the condition of $L_6$.

For determination of the sign of the correction $\Delta S_{\delta}$ when the physical period of the pendulum is close to 1 sec, a stopwatch may be used (25). The latter starts simultaneously with the impulse, stopping the count with the measurement of asymmetry. Noting how the half-period (large or small) is fixed by the counting device, the timer starts simultaneously with the impulse, beginning count with the measurement of the period of oscillation of the pendulum. Depending on whether the timer started on a whole second or a half-second, the sign of the correction is determined, making use of Table 3, which is readily obtained from Fig. 8.

It is also possible to determine the sign of the correction for asymmetry if an auxiliary counting device is used, with which would be measured the half-period (large or small) of oscillation of the pendulum, and which would begin the count simultaneously with the main counting device.

For some types of pendulum apparatus (for example, the OVM apparatus) it is possible to make the asymmetry negligibly small with the aid of adjusting elements. In this case the question arises of introducing control of the asymmetry and its correction if it attains a significant magnitude. In Table 4 are presented the limits permitted for the asymmetry for which the corresponding correction to the period will be less than 5 x $10^{-9}$s.

## V. Accuracy of measurement of amplitude by the photo-electric method

The amplitude of oscillation of the pendulum can be determined by the known formula

$$a = (y - y_0)/\sin[2\pi(t - t_0)/T],$$

where y is the angle of inclination of the pendulums from the position of equilibrium;

a is the amplitude of oscillation of the pendulum;

$t_0$ is the initial time corresponding to a passage of the pendulum through the equilibrium position;

t is the elapsed time;

T is the period of the pendulum.

In (3) it is shown that if this formula is written for the instants $t_1$, $t_2$, and $t_3$, in which y has the corresponding values $y_1$, $y_2$, and $y_3$, then the amplitude of oscillation of the pendulum is easy to obtain, without knowing the moment $t_0$ and the equilibrium position of the pendulum $y_0$ corresponding to t.

Whereas with photographic recording the intervals of time $t_3 - t_2 = t_2 - t_1 = 0.1$s are fixed (31), and $(y_3 - y_2)$ and $(y_2 - y_1)$ are measured from the photograph, on the other hand, in the photo-electric method $y_3 - y_2$ and $y_2 - y_1$ are fixed, and the intervals of time $t_3 - t_2$ and $t_2 - t_1$ are measured with the aid of a counting device. The problem of determining the amplitude of oscillation of the pendulums is very much simplified if $y_2$ is chosen so that $y_3 - y_2 = y_2 - y_1$. Such a choice corresponds to a symmetrical disposition of $y_1$ and $y_3$ relatively to the equilibrium position of the pendulum. In this case the amplitude of oscillation of the pendulum can be determined from the formula

$$a = \frac{l}{2\sin[\pi(t_3 - t_1)/2S]}$$

where l is the fixed (angular) distance between the two slits, symmetrically located with respect to the third slit on which the image of the transmitting diaphragm is projected after reflection from the pendulum, when the latter is located in the equilibrium position.

The requirements regarding asymmetry are not so high for determination of the amplitude as for the period of the pendulum. In Table 5 is shown the asymmetry which can be tolerated so that the error in the amplitude does not exceed $5 \times 10^{-9}$s.

In construction of the table it is assumed that the equivalent focal distance of the objective is 540 mm, and that l = 3.6 mm.

For the typical accuracy of determination of the amplitude with the photo-electronic recorder we present a table of results of measurements of the amplitude of the fictitious pendulum. A measurement is carried out each 30 s over an interval of 33 min (Table 6).

The logarithmic decrement of damping was determined as $\lambda = 0.0000363\ s^{-1}$ on the basis of the observations. Then, the amplitude is calculated for selected instants from the familier formula.

$$a = a_o e^{-\lambda t}$$

where $a_o$ is the amplitude at the initial instant t = 0, and e = 2.71 is the base of the natural logarithms.

The accuracy of the amplitude was evaluated from the difference between observed and calculated values. The accuracy obtained was higher than required for calculation of the correction to the amplitude with a mean-square error of $\pm 5 \times 10^{-9}$s.

## VI. Future improvements in the method of photo-electric recording

One of the deficiencies in the method described for determination of the period of the pendulum is the fact that only one impulse is used for opening and closing a series of observations. Therefore a chance disturbing effect on the pendulum at this moment, caused for example by external influences (microseisms, vibrations, etc.), can noticeably alter the measured period of oscillation. In order to reduce the influence of random errors without increasing the duration of the observations, a series of observations must use not one, but several successive impulses at the time of recording.

For pendulum measurements of gravity on moving bases (on moving boats and surface vessels) the instantaneous value of the phase of the pendulum essentially depends on the magnitude of the disturbing vertical accelerations. In order to diminish the influence of the latter, as is well known, it is necessary to record the phase of the pendulums at the beginning and end of a series of observations during an interval of time equal to the period of the disturbing acceleration.

If the period of a pendulum on a moving base is determined by photographic recording, the results of the measurements are averaged partly by a graphical and partly by an analytical method. In order to use the photo-electronic method it is necessary to use at the beginning and end of a series of observations as many successive impulses as are contained in a full period of the disturbing accelerations, i.e. to use not one, but several channels of the counter. If, for example, the period of the waves is 8 s, then in the analysis of the readings eight channels must be used for calculation of the period. The average of these is largely free of the influence of vertical accelerations (to the first order).

In the gravimetric laboratory a suitable averaging device, containing an eight-channel counter, has been developed (Fig. 9). It has been made in the form of an attachment to the photo-electronic recorder described above. Each channel of this device consists of a trigger for opening and closing the counter, a pulse gate, and a counting device. The last has a small-capacity counter in order to determine only small changes in the period caused by the disturbing factors. The full period is measured by the counting device FR. The triggers for starting and stopping the counter, and also the pass-through cascade for each channel, make use of the valves 6N1P.

A supplementary channel ("Asymmetry") is introduced in this device. Measurements made at the beginning and end of a series of observations permit determination of the magnitude and sign of the correction for asymmetry.

The shaping cascade and the rectangular impulse generator with frequency of 100 kHz are located within the body of the photo-electronic recorder. The signal on the averaging device is drawn from the anode of the two-channel amplifier-limiter ($L_5$ in Fig. 3) through the junction ShR1, while for starting the count the signal coming from the left half, and for stopping the count from the right half, of one and the same valve is used. The duration of the observations is set by the photo-electronic recorder FR. The opening (closing) of the first channel of the averaging device is effected after the opening (closing) of the counter FR through an interval of time equal to the full period of the oscillation 2S, the second channel through 4S, the third through 6S, etc.

In starting a series of observations the contacts 1 and 2 of the change-over switch Vk5 are closed. In this condition the impulse opening the counting device FR passes through the second plate of the step selector ShI-11 on the outlet device $A(L_7)$, which opens the corresponding pulse gate $L_8$.

The counting device "Asymmetry" starts counting impulses from the quartz generator (100 kHz), activated by FR. This same impulse passes through the fifth plate of ShI-11 to the divider, introducing its own binary stage $L_6$. The winding of relay RPS-5 is located at the anode of the binary stage. The latter operates the step selector through the power relay RSM-1. Since an impulse is admitted to the divider each half-second, then also the $RP^S$-5 will open and close every half-second.

The second impulse also puts the outlet device A into the conducting state through the second plate. The half-period of oscillation of the pendulums from which the measurement on FR was begun, will then be determined on the counting device "Asymmetry". This same impulse throws over the binary stage, as a result of which the first plate of ShI-11 goes into state 2.

The next impulse with the aid of the outlet device 1 ($L_9$) opens the pulse gate ($L_{17}$) and the counting device for I channel begins counting. In Fig. 9 the outlet device and the pulse gate corresponding to it have the same number as the number of the channel. The fourth-impulse drives the plate of ShI-11 into stage 3, and the next impulse starts the counting device II, etc, until such time as the step selector will not go into states 1, 1 and 12, 5. No further impulses will be admitted to the divider and the step selector will remain in the closed state.

Now it is necessary to transcribe the indication of the counting device "Asymmetry", completing the break and disconnecting the rectifier by the toggle-switch Vk-3. Not long before the closing series of observations the contacts 3 and 4 are closed by the change-over switch Vk-5 and the rectifier is connected. After this event, the plates ShI-11 go into state 2.

The first stopping impulse from the second anode of the two-channel amplifier FR goes through the second plate on the outlet device ($L_7$), which opens the corresponding pulse gate. The counting device "Asymmetry" begins to count. The impulse described above through the fifth plate proceeds also to the divider.

The second closing impulse also through the second plate drives the outlet device A into the conducting state, and that same half-period of oscillation of the pendulum which was measured at the beginning of the series of observations, will be recorded on the counting device "Asymmetry". This same impulse throws over the binary stage $L_6$, and therefore the first plate goes into stage 2.

The third impulse takes the outlet device I into the conducting state, and the counting device I channel stops counting. The next impulse drives the step selector into state 3 and the same prepares the second channel for closing etc., until such time as all the counting devices will not count.

A general picture of the averaging device is shown in Fig. 10. The power supply, the triggers for starting and stopping the count, and the pulse gates are arranged on the chassis of the apparatus. The counting device consists of two almost identical blocks, which in case of necessity can be substituted as spares.

Inzh. M.G. Kogan, Inzh. V.V. Kukhov, and Sen. Tech. Yu. A. Moiseev took part in carrying out the experiments described.

Inzh. V.P. Terekhov and V.I. Fomin took part in the manufacture and adjustment of the averaging device. To all of these the author expresses deep appreciation.

## TABLE 1

16 JAN. 1966

Pendulum apperatus 6302
Photo-electronic recorder FP-03

| No. | Period sec | Departure from average | No. | Period sec | Departure from average | No. | Period sec | Departure from average |
|---|---|---|---|---|---|---|---|---|
| 1 | 0,98211 | -1,3 | 18 | 0,98211 | -1,3 | 35 | 0,98210 | -0,3 |
| 2 | 211 | -1,3 | 19 | 209 | +0,7 | 36 | 208 | +1,7 |
| 3 | 211 | -1,3 | 20 | 208 | +1,7 | 37 | 212 | -2,3 |
| 4 | 210 | -0,3 | 21 | 210 | -0,3 | 38 | 209 | +0,7 |
| 5 | 210 | -0,3 | 22 | 209 | +0,7 | 39 | 210 | -0,3 |
| 6 | 209 | +0,7 | 23 | 208 | +1,7 | 40 | 210 | -0,3 |
| 7 | 210 | -0,3 | 24 | 210 | -0,3 | 41 | 211 | -1,3 |
| 8 | 211 | -1,3 | 25 | 211 | -1,3 | 42 | 211 | -1,3 |
| 9 | 210 | -0,3 | 26 | 210 | -0,3 | 43 | 210 | -0,3 |
| 10 | 207 | +2,7 | 27 | 207 | +2,7 | 44 | 209 | +0,7 |
| 11 | 209 | +0,7 | 28 | 211 | -1,3 | 45 | 209 | +0,7 |
| 12 | 208 | +1,7 | 29 | 211 | -1,3 | 46 | 209 | +0,7 |
| 13 | 211 | -1,3 | 30 | 209 | +0,7 | 47 | 211 | -1,3 |
| 14 | 210 | -0,3 | 31 | 209 | +0,7 | 48 | 208 | +1,7 |
| 15 | 210 | -0,3 | 32 | 209 | +0,7 | 49 | 210 | -0,3 |
| 16 | 209 | +0,7 | 33 | 210 | -0,3 | 50 | 211 | -1,3 |
| 17 | 210 | -0,3 | 34 | 211 | -1,3 | | | |

Average - 0,98209
$m = \pm 11,5.10^{-6}$ sec

## TABLE 2

| No. | Date 1964 | Time | Average Pressure mm Hg | Periods sec 1 | 2 | 3 | 4 | 5 | 6 | Av. | Mean square error of series |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 10/XII | 6h 16m | 0,55 | 0,49397950 | 47 | 47 | 46 | 48 | 40 | 46 | ±3,4 |
| 2 | | 18 40 | 0,50 | 53 | 52 | 58 | 47 | 42 | 46 | 50 | 5,8 |
| 3 | | 23 10 | 0,45 | 59 | 51 | 54 | 52 | 52 | 56 | 54 | 3,0 |
| 4 | 11/XII | 3 30 | 0,50 | 50 | 47 | 45 | 46 | – | 42 | 46 | 2,9 |
| 5 | | 17 10 | 0,50 | 45 | 47 | 47 | 46 | 46 | 44 | 46 | 1,2 |
| 6 | | 22 25 | 0,55 | 52 | 49 | 48 | 48 | 47 | 47 | 48 | 1,9 |
| 7 | 12/XII | 2 40 | 0,55 | 44 | 47 | 38 | 41 | 40 | 40 | 42 | 3,3 |
| 8 | | 7 10 | 0,55 | 48 | 48 | 51 | 53 | 52 | 41 | 49 | 4,4 |
| 9 | | 17 30 | 0,60 | 49 | 54 | 49 | 52 | 54 | – | 52 | 2,5 |
| 10 | 13/XII | 9 45 | 0,55 | 48 | 50 | 47 | 45 | 49 | 42 | 47 | 2,9 |
| 11 | | 14 20 | 0,50 | 42 | 41 | 43 | 38 | 41 | 38 | 40 | 2,1 |
| 12 | 14/XII | 6h 55m | 0,55 | 47 | 47 | 49 | 50 | 49 | 51 | 49 | 1,6 |

TABLE 3

| Measured half-period | Whole number sec | Multiple (n+0.5), sec | Remark |
|---|---|---|---|
| Large . . . . . . . . . | - | + | Integer |
| Small . . . . . . . . . | + | - | Number of seconds |

TABLE 4

| Initial amplitude | a = 40' | a = 20' | a = 6' |
|---|---|---|---|
| $\delta_l$ | 0,012 | 0,008 | 0,002 |

TABLE 5

| Asymmetry, mm | Amplitude of Pendulums | | |
|---|---|---|---|
| | 40' | 20' | 6' |
| 0,5 | $1{,}4.10^{-9}$ | $1{,}7.10^{-9}$ | $2{,}1.10^{-9}$ |
| 1,0 | $6{,}4.10^{-9}$ | $6{,}7.10^{-9}$ | $8{,}6.10^{-9}$ |

TABLE 6

$\lambda$ = 0,00003628

| Time | Amplitude measured | Amplitude calculated | Difference | Time | Amplitude measured | Amplitude calculated | Difference |
|---|---|---|---|---|---|---|---|
| 0m 00s | 1388",4 | | | 18m 00s | 1335",2 | 1334",4 | +0"8 |
| 30 | 87 ,1 | 1386",9 | +0",2 | 30 | 33 ,8 | 32 ,9 | +0 ,9 |
| 1 00 | 84 ,5 | 85 ,3 | -0 ,8 | 19 00 | 31 ,2 | 31 ,5 | -0 ,3 |
| 30 | 83 ,5 | 83 ,8 | -0 ,3 | 30 | 29 ,8 | 30 ,0 | -0 ,2 |
| 2 00 | 82 ,9 | 82 ,3 | +0 ,6 | 20 00 | 28 ,1 | 28 ,5 | +0 ,4 |
| 30 | 79 ,5 | 80 ,8 | -1 ,3 | 30 | 27 ,0 | 27 ,1 | -0 ,1 |
| 3 00 | 79 ,1 | 79 ,2 | -0 ,1 | 21 00 | 26 ,2 | 25 ,6 | +0 ,6 |
| 30 | 78 ,7 | 77 ,7 | +1 ,0 | 30 | 23 ,7 | 24 ,1 | -0 ,4 |
| 4 00 | 75 ,5 | 76 ,2 | -0 ,7 | 22 00 | 23 ,5 | 22, 7 | +0 ,8 |
| 30 | 74 ,7 | 74 ,7 | 0 ,0 | 30 | 22 ,2 | 21 ,2 | +1 ,0 |
| 5 00 | 72 ,8 | 73 ,2 | -0 ,4 | 23 00 | 20 ,9 | 19 ,8 | +1 ,1 |
| 30 | 72 ,0 | 71 ,7 | +0 ,3 | 30 | 18 ,0 | 18 ,3 | -0 ,3 |
| 6 00 | 70 ,3 | 70 ,2 | +0 ,1 | 24 00 | 16 ,1 | 16 ,9 | -0 ,8 |
| 30 | 68 ,2 | 68 ,7 | -0 ,5 | 30 | 15 ,1 | 15 ,4 | -0 ,3 |
| 7 00 | 66 ,9 | 67 ,1 | -0 ,2 | 25 00 | 14 ,8 | 14 ,0 | +0 ,8 |
| 30 | 66 ,5 | 65 ,6 | +0 ,9 | 30 | 12 ,8 | 12 ,5 | +0 ,3 |
| 8 00 | 63 ,1 | 64 ,1 | -0 ,1 | 26 00 | 10 ,9 | 11 ,1 | -0 ,2 |
| 30 | 61 ,7 | 62 ,6 | -0 ,9 | 30 | 08 ,8 | 09 ,6 | -0 ,8 |
| 9 00 | 61 ,7 | 61 ,1 | +0 ,6 | 27 00 | 08 ,4 | 08 ,2 | +0 ,2 |
| 30 | 59 ,1 | 59 ,6 | -0 ,5 | 30 | 07 ,1 | 06 ,8 | +0 ,3 |
| 10 00 | 58 ,7 | 58 ,7 | +0 ,6 | 28 00 | 05 ,6 | 05 ,3 | +0 ,3 |
| 30 | 57 ,3 | 56 ,6 | +0 ,7 | 30 | 05 ,0 | 03 ,9 | +1 ,1 |
| 11 00 | 55 ,8 | 55 ,1 | +0 ,7 | 29 00 | 02 ,0 | 02 ,4 | -0 ,4 |
| 30 | 54 ,1 | 53 ,7 | +0 ,4 | 30 | 01 ,6 | 01 ,0 | +0 ,6 |
| 12 00 | 51 ,6 | 52 ,2 | -0 ,6 | 30 00 | 1300 ,0 | 1299 ,6 | +0 ,4 |
| 30 | 50 ,8 | 50 ,7 | +0 ,1 | 30 | 1297 ,9 | 98 ,1 | -0 ,2 |
| 13 00 | 48 ,6 | 49 ,2 | -0 ,6 | 31 00 | 97 ,4 | 96 ,7 | +0 ,7 |
| 30 | 47 ,6 | 47 ,7 | -0 ,1 | 30 | 94, 9 | 95 ,3 | -0 ,4 |
| 14 00 | 46 ,6 | 46 ,2 | +0 ,4 | 32 00 | 94 ,1 | 93 ,9 | +0 ,2 |
| 30 | 44 ,0 | 44 ,8 | -0 ,4 | 30 | 92 ,8 | 1291 ,4 | +0 ,4 |
| 15 00 | 43 ,0 | 43 ,3 | -0 ,3 | 33m 00s | 1291 ,0 | | |
| 30 | 42 ,1 | 41 ,8 | +0 ,3 | | | | |
| 16 00 | 41 ,1 | 40 ,3 | +0 ,8 | | | | + 19",2 |
| 30 | 38 ,4 | 38 ,8 | -0 ,4 | | | | - 15",9 |
| 17 00 | 35 ,8 | 37 ,3 | -1 ,5 | | | | |
| 17m30s | 1335 ,0 | 1335 ,9 | -0 ,9 | m = ±0",63 | | | |

## ILLUSTRATIONS

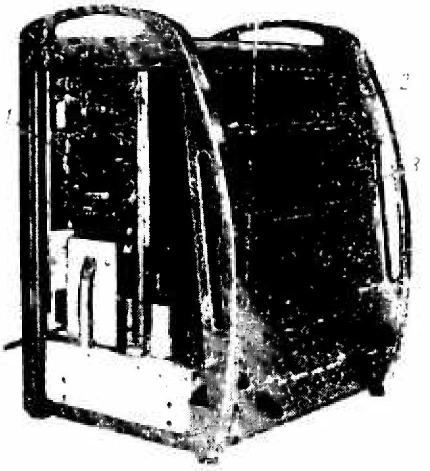

Fig. 1 PHOTO-ELECTRIC RECORDER (FRONT VIEW)

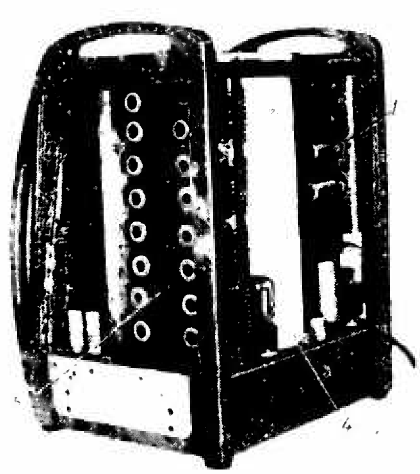

Fig 2 PHOTO-ELECTRIC RECORDER (REAR VIEW)

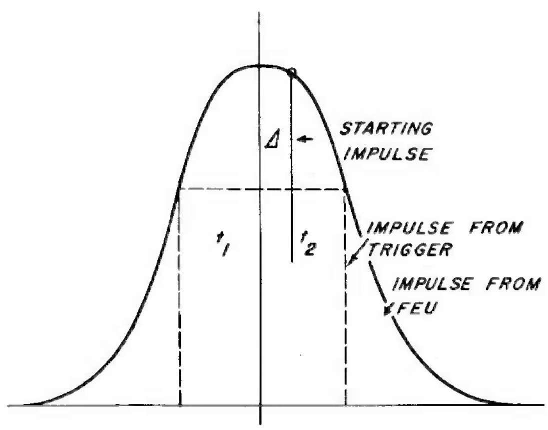


Fig 4 BELL-SHAPED IMPULSE FROM PHOTO-ELECTRIC MULTIPLIER

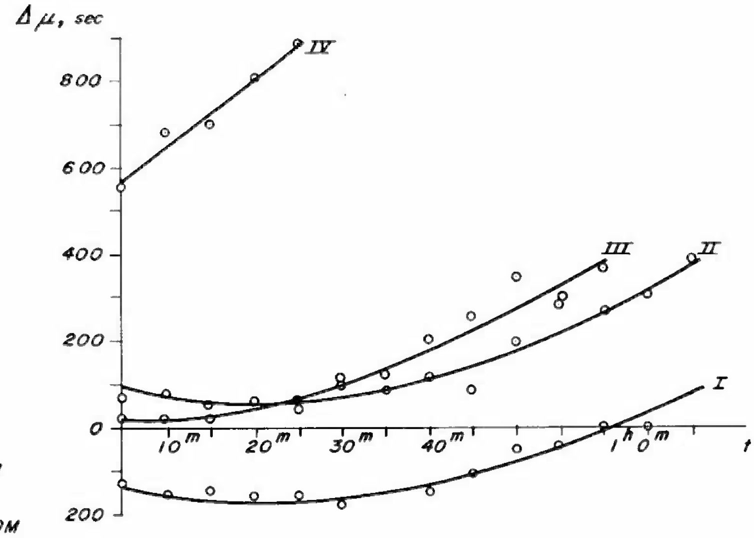


Fig. 5 DETERMINATION OF THE VALUE OF Δ ($C_3$= 51 pF).

I- WITH MINIMAL THRESHOLD OF TRIPPING OF THE PASSIVE MULTIVIBRATOR; II and III - WITH THRESHOLD OF TRIPPING EQUAL TO 1 VOLT; IV - WITH MAXIMAL THRESHOLD OF TRIPPING

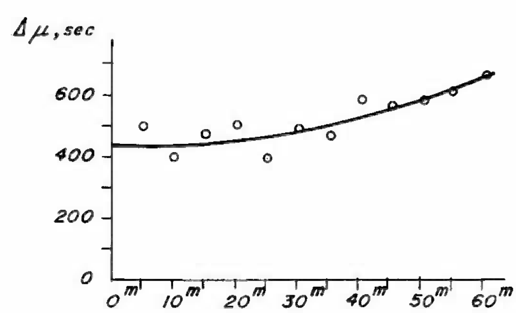


Fig 6 DETERMINATION OF THE VALUE OF Δ ($C_3$=430 pF)

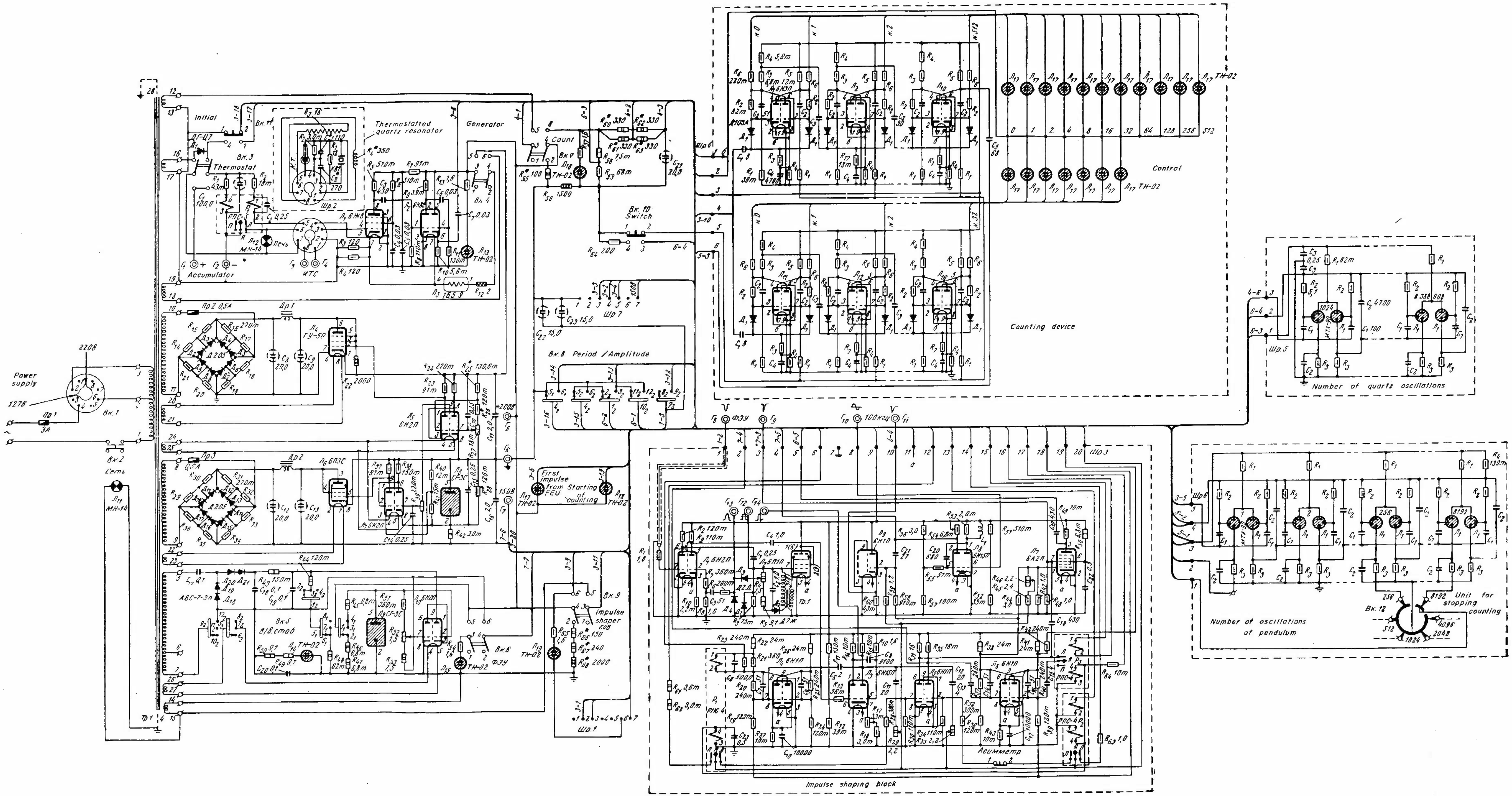



Fig. 3 CIRCUIT DIAGRAM OF PHOTO-ELECTRIC RECORDER

To Accompany Record No. 1973/119

G65-360

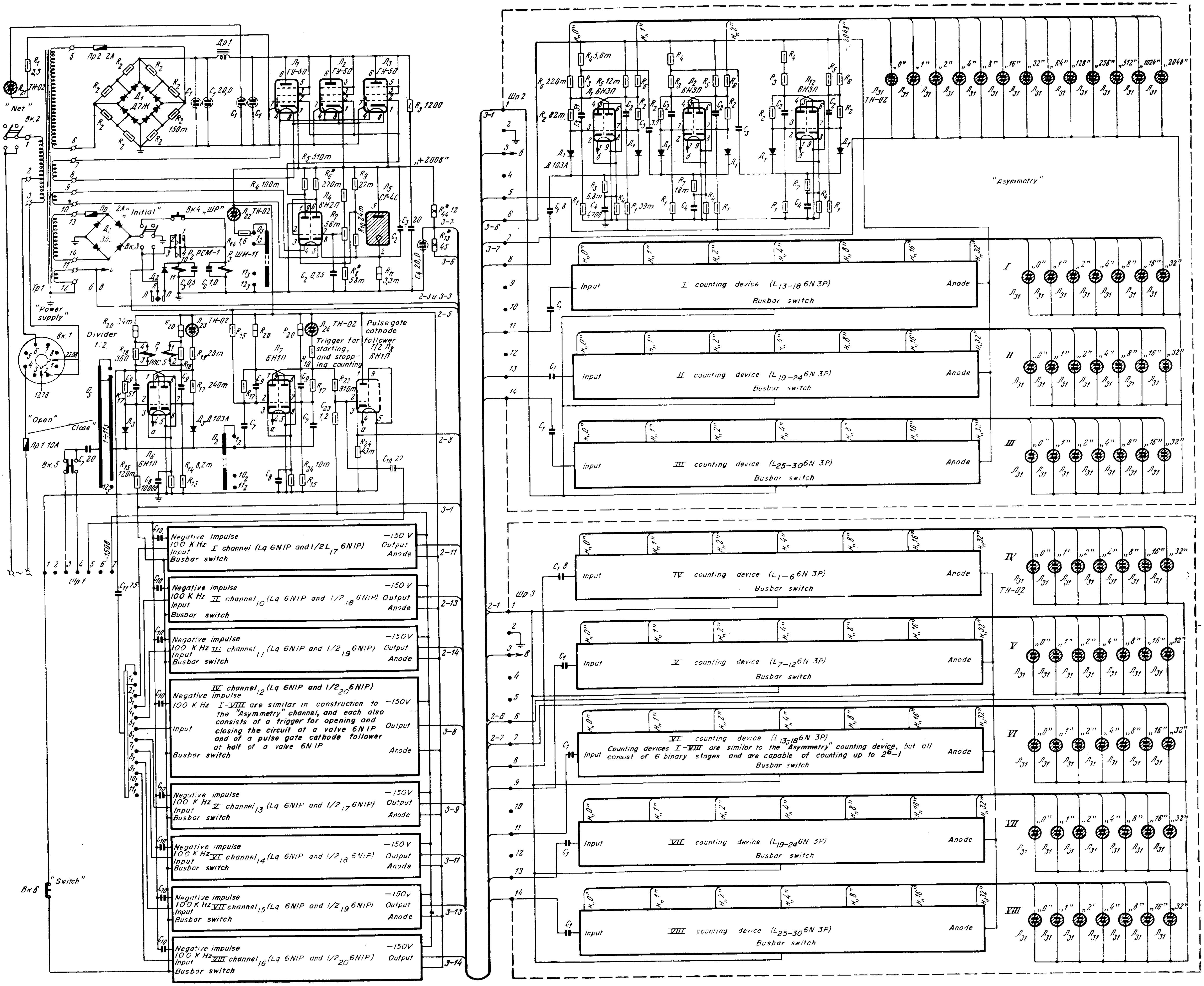


Fig. 9 CIRCUIT DIAGRAM OF THE AVERAGING DEVICE

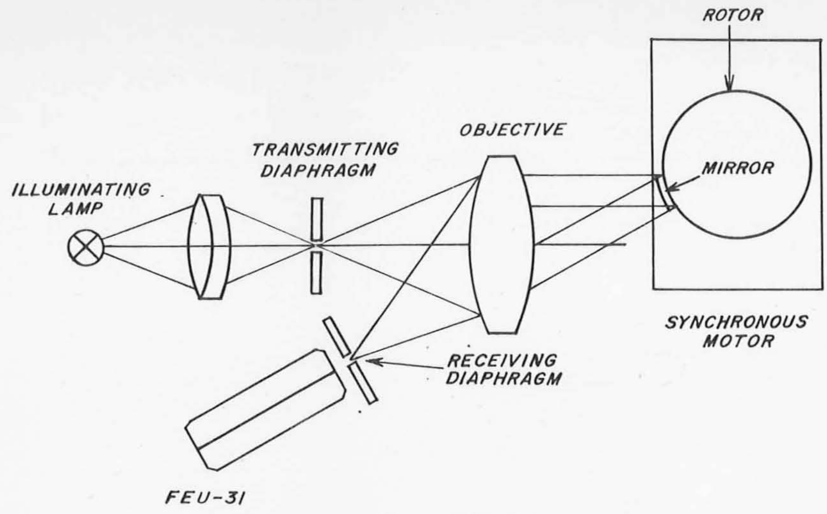


Fig. 7 SYNCHRONOUS MOTOR – TRANSDUCER OF STABLE IMPULSE

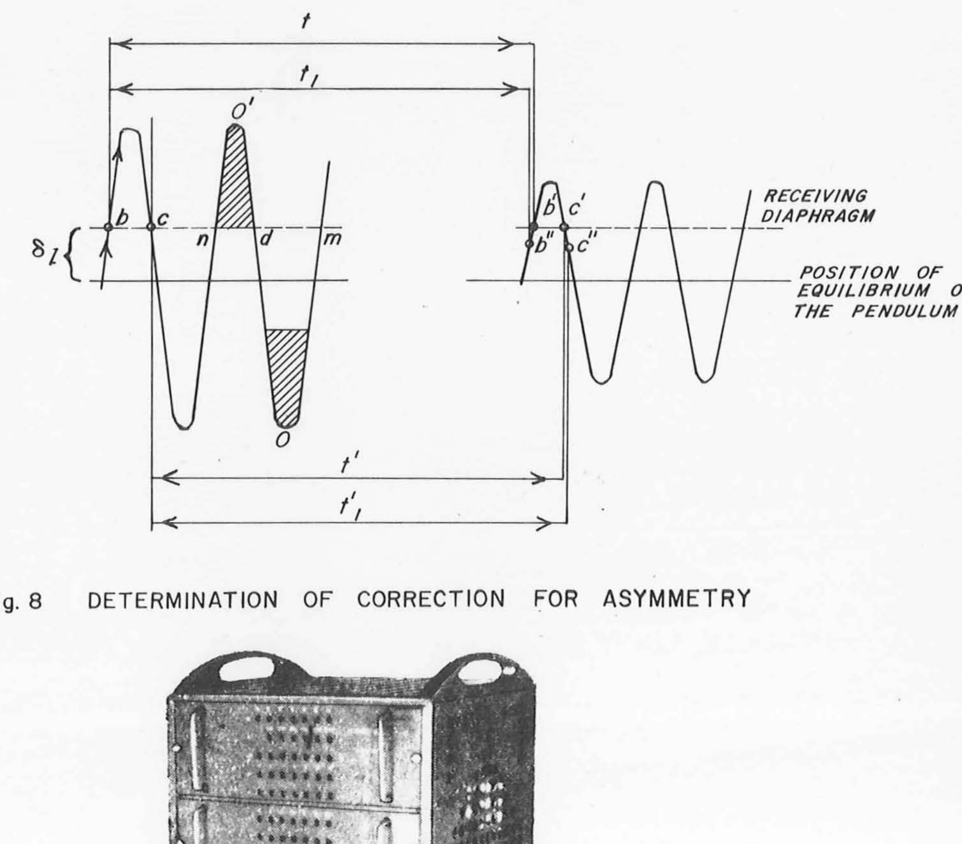


Fig. 8 DETERMINATION OF CORRECTION FOR ASYMMETRY

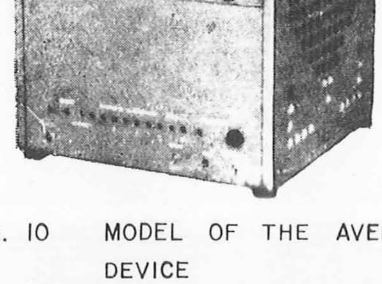

Fig. 10 MODEL OF THE AVERAGING DEVICE

TsNIIGAiK

# Experimental work with the vacuum pendulum apparatus

Yu. A. SLIVIN

(p.90)


Summary

The principal features of a set of OVM pendulum apparatus are described, and also the results of its testing, the method of determination of high-accuracy pendulum stations, and the results of experimental measurements at three points.

Discrepancies between the results of measurements with OVM and VMP apparatuses do not exceed 0.20 mGal.

The mean-square error in determination of g by one unit of the OVM set, calculated from the agreement of units at stations, is ± 0.22 mGal, corresponding to 0.13 mGal for a set of three units.

(8 tables, 5 illustrations)

## General Comments

Results of measurements of gravity obtained withhigh-accuracy VMP pendulum apparatus TsNIIGAiK, and a description of the apparatus, are presented in references (31) and (35). From these it follows in particular that pendulum measurements of gravity do not attain the accuracy of gravimetric measurements (referring to "geodetic" gravity meters).

However, the VMP was developed with the chief purpose of attaining the theoretical possibilities of the pendulum method, and therefore it has a number of deficiencies limiting the scope of its application. We note the following basic deficiencies: (1) the apparatus is not evacuated, therefore it is difficult to use in mountainous regions, and in general at stations where the atmospheric pressure changes substantially from the pressure at the base station; (2) the oscillations of the pendulums are recorded on photographic film, and the observational procedure is quite laborious.

The problem of removing these deficiencies became particularly significant in connexion with certain important and interesting comparisons made during analysis of the results of work with the VMP at stations where parallel observations were carried out with GAE gravity meters, developed in the Institute of Physics of the Earth of the Academy of Sciences, USSR. These comparisons and the conclusions from them are described in detail in (35). We recall that the results of the analysis showed:

(1) The mean-square error of measurements with the VMP set did not exceed $\pm$ 0.2 mGal independently of the distance between the station and the base.

(2) Results obtained with the quartz-metallic pendulums differed systematically from those of the GAE gravity meters, as a linear function of gravity of the order of 0.6 mGal/Gal. This conclusion was based on measurements over an interval of almost 3 Gal. Theoretically the results from pendulums and from GAE gravity meters should be expressed directly as cgs units.

The systematic discrepancy between the pendulum and gravity meter measurements is well established, as it is based on a large number of measurements at various stations and at various times. Comparisons at 18 points were carried out over a period of 15 years; high precision measurements with the VMP set were carried out at 7 points, at each of which observations were made at least twice, at intervals from several months to several years.

It is very important to explain these systematic discrepancies. First of all the question arises, is the explanation of the discrepancies of the results obtained such, that no pendulum measurements should be carried out without evacuation of the apparatus. Insofar as the pressure of the atmosphere at stations can be correlated with gravity, this discrepancy might cause errors in the barometric coefficient of the pendulums. Some doubt can also arise from the fact that all pendulum measurements intended for comparison with gravity meters were carried out with quartz-metallic pendulums, even though in various types of equipment. Finally, it is possible that the classical theory of oscillations of pendulums is not accurate enough to explain the results of observations of increasing accuracy.

Similar requirements for a review of the theory and methods of measurement can arise in relation to gravity meters. It is essential that the specialists engaged in development of pendulum and gravity meter apparatus must thoroughly examine these questions.

The gravimetric laboratory TsNIIGAiK, continuing traditional investigations for improvement of the pendulum method of measurement, began the appropriate new developments as early as 1961. In the new apparatus (by comparison with VMP) built in the laboratory, the following basic improvements were introduced:

1. The apparatus was evacuated to such a degree that the influence of errors of the barometric coefficient of the pendulums was fully excluded.

2. Photo-electric recording of the period and amplitudes of oscillation of the pendulums was used, as a result of which the duration of the observations was significantly reduced.

3. Processing of the observations and treatment of the data were automated to such an extent that the measurements can be checked immediately at the time of observation at the station. The apparatus is remotely controlled.

4. The construction of the apparatus was significantly improved, particularly in respect of the accuracy of lowering the pendulums onto the agate flats.

In 1964 the laboratory investigations produced a prototype of the vacuum pendulum apparatus (OVM) and in 1965 the acceleration due to gravity was determined at several stations on the basic gravity meter net of USSR. On the basis of the investigations certain methods of observations were worked out, and the most important merits and deficiencies of the apparatus were demonstrated; the latter were removed later.

As regards the accuracy obtained, it was shown that for the influence of random errors it was close to that of the VMP set. The data accumulated are still inadequate for judgement on the systematic errors, inasmuch as all observations were carried out in a relatively small interval of gravity (less than 0.5 Gal).

It is proposed to make determinations with the sets OVM and VMP over a large gravity interval (about 2 Gal), and further, under large variations in atmospheric pressure.

Full evaluation of the accuracy and merits of the new apparatus can be compiled after accumulation of experimental operation under various conditions. However, preliminary data can be useful, not only for critical evaluation of the principles postulated in the basic construction of the new apparatus and the method of operating it, but also for the supplementary characteristics of the accuracy of measurement achieved with various gravity meter apparatuses. In this plan, a new comparison with gravity meter measurements will also be very interesting.

## I. Brief introduction to the set of equipment

The set of equipment OVM consists of three double-pendulum apparatuses. In apparatuses No. 6101 and 6103, which in the following will be designated respectively No. 1 and 2, quartz-metallic pendulums with tungsten bobs are used, while in apparatus No. 6302, designated as No. 3, quartz-bronze minimum pendulums are used. The set of equipment is shown in Fig. 1.

Distinctive features of these apparatuses are, that they are evacuated, and all control of the pendulums inside the equipment is carried out from a panel, making use of a special reversible electric motor. With motion of the rotor of the motor in one direction, the pendulums are clamped, i.e. they are moved into position for transport. When the rotor moves in the reverse direction, the pendulums are firstly unclamped and centred. A constant landing position of the pendulums on the flat is guaranteed by this centring device with an accuracy of $\pm 1\,\mu$. With further motion of the rotor the pendulums are deflected by a master cam from the equilibrium position by an angle 1.5 to 2 times larger than the amplitude of vibration, i.e. by an angle of approximately 40–60'. The pendulum is landed on the operating flat in this deflected position, after which the angle of inclination is decreased to the initial amplitude, and the pendulum is then set in motion. Simultaneously with the release the electric motor is also stopped. In arresting the pendulums subsequently, they are firstly stopped by a special device, and then removed from the agate flats also in the inclined position.

Construction of the starting device in apparatus No. 2 is such that both pendulums are simultaneously assigned an initial amplitude equal to either 48', 23' or 6.5', with opposite phases. For the two other sets, the initial amplitude was close to 20'. The program of operation of the starting device can be changed only under laboratory conditions. For determination of the periods of the separate pendulums one pendulum of the pair must be set to a null amplitude. To this end, after starting the pendulums (or on completion of the observations over an interval of a sequence) one of them was stopped by a special device controlled from the panel. Different intervals of the observations, as also with VMP, were separated by arresting. After completion of observations at a point, the reverse motion of the motor was switched on, and the pendulums were clamped for transport to the next point.

In the periods between separate intervals of measurement, when necessary the air was evacuated from the apparatus by means of an oil vacuum pump, maintaining pressure constantly below 0.2 mm Hg. Observations were carried out with average pressures of 1.3, 0.4, and 0.9 mm Hg respectively for sets No. 1, 2,and 3. Usually the rate of change of pressure inside the apparatus did not exceed 0.01 mm Hg per hour, while the duration of one of a series of observations amounts to 17 min. Evacuation of the air was carried out every 2–4 hours. At the time of evacuation the temperature within the thermostatted volume of the apparatus did not change.

The air pressure within the apparatus was checked by a resistance vacuum gauge. The sensitive element was the transducer MT-6.

The temperature in the apparatus was measured by a thermistor with sensitivity of the order of 0.02°C. The thermostat temperature for sets No. 2 and 3 was 35°C, and for No. 1, 40°C.

In apparatus No. 2 a photomultiplier FEU was fixed inside the evacuated volume. The electrodes were isolated by epoxy resin; independent electrical discharge did not occur between them if the pressure did not exceed 0.8 mm Hg. The FEUs were attached outside the apparatus in sets No. 1 and 2.

The focusing distance of the objective of sets No. 1 and 2 is 135 mm, and for No. 3, 149.3 mm. The corresponding focusing distance for VMP is almost 8 times this distance. Optical multiplication of the angle of declination of the fictitious pendulum was used to increase the length of the optical lever; this is effected in sets No. 1 and 3 by five-fold reflection of the ray from the mirrors of both pendulums of a pair, while for No. 2, a four-fold reflection is used. This application of optical multiplication enables unified construction of the pendulum apparatus with the light source and the transducer of impulses from the pendulum oscillations.

In general the OVM set is much more compact than the VMP set. The dimensions of the equipment are less, not only on account of the use of quartz-metallic pendulums with tungsten bobs (34), but also on account of the more rational construction. Thanks to the high specific gravity of tungsten, the volume of the bob of the pendulum is almost halved while preserving the weight of the previous bob. Therefore the barometric coefficient is also almost halved.

For apparatus No. 3 a pendulum was built, substantially differing not only in shape and dimensions from the pendulums of sets No. 1 and 2, but also in the material from which the bobs and heads were constructed. This type of pendulum is completely insensitive to the influence of magnetic fields. The pendulums used are shown in Fig. 2, and the pendulum of the VMP apparatus is shown also for comparison.

For determination of the periods and amplitudes of the pendulums, a photo-electronic recorder FR was used (see Fig. 77) (1), (27), (28), which was combined in construction with the 100 kHz quartz oscillator. Readings of the counting device of the FR are computed for determination of the period and amplitude of the pendulum oscillations, and such data as are needed for introduction of the correction for asymmetry.

All counts taken with the FR were expressed in the binary system, but conversion to decimals does not present any difficulty.

Since the pendulums are not removed from the apparatus, setting up at a station and observing are relatively quick and simple. Inasmuch as the apparatus is thermostatically controlled and to a high degree hermetically sealed, and the initial amplitude and phase are set in a very uniform way, the value of corresponding corrections to the period of the pendulums at various stations is nearly constant. Therefore the analysis of the observational data is particularly easy.

In the 1965 operations, besides the apparatus described above, the VMP set was used (35), (31). In order to simplify considerably the treatment of the observational data, a photo-electric adapter FP was developed for this set; in conjunction with the FR this enabled measurement of the periods and amplitudes of the pendulums by the photo-electronic method. Essentially this device introduces its own adapter, which can be used for operation with any pendulum apparatus having an inspection window for observations.

In 1964-65 the constants of all sets of apparatus were determined. Without dwelling on the method of these determinations we will present their results.

The barometric coefficient was determined from observations in the range of air pressure from 0.5 to 16 mm Hg with constant temperature thermostatted to +35°C or +40°C. In this pressure interval the change of period can be taken as linear.

In Table 1, the temperature and barometric coefficients of the pendulums, and the value of the barometric coefficient of the VMP pendulums in this pressure interval, are presented.

TABLE I

| No. of Apparatus | Coefficients | |
|---|---|---|
| | Temp., s/°C | Barom., s/mm Hg |
| 1 | $9.0 \times 10^{-8}$ | $7.5 \times 10^{-8}$ |
| 2 | 12.8 | 7.5 |
| 3 | 40.0 | 15.6 |
| VMP | 30.0 | 14.0 |

## II. Some features of the operation of the pendulum apparatus

With photo-electric recording of the periods and amplitudes of oscillation of the pendulums, the optical adjustment of the apparatus must be carried out more carefully. In particular, specific attention was devoted to the magnitude of asymmetry $\delta t$ (see p. ). The latter was corrected by adjustable elements of the pendulum apparatus OVM, or the photo-electric adapter for the VMP. In the observational procedures care was taken that the correction for asymmetry did not exceed $0.5 \times 10^{-8}$ s.

The method of operation with the OVM set differs from that with the other sets mainly in the method of calculating the correction for amplitude.

With photographic recording of the oscillations of the pendulums, the amplitude of oscillation of both actual and fictitious pendulums are determined at one and the same moment. Experiment has shown that, with good synchronization of the pendulums, equal initial amplitudes, and simultaneous starting, the amplitude of the fictitious pendulum is equal to the sum of the individual amplitudes of the actual pendulums to a high degree of accuracy, throughout the duration of the observations. Thus only the amplitude of the fictitious pendulum need be measured; this simplifies the measuring procedure and the corresponding construction of the apparatus. Good checks of the control of the above assumptions are firstly, stability in the correction for amplitude applied to the periods obtained in various series of observations, and secondly, stability of these periods.

As stated above, the residual pressure inside the OVM sets was measured with a valve MT-6. Before the beginning of operations the latter was calibrated by means of comparison of the readings of vacuum meter and a manometer. In order to indicate various types of systematic errors, an attempt was made to carry out all observations with one and the same pressure.

With photo-electronic recording of the periods of oscillations of the pendulums the observation time was reduced; therefore a higher accuracy was required of the quartz chronometer. Stability of the rate of the quartz oscillator used in FR did not completely meet the increased requirements; therefore at the time of the experimental work in 1965, systematic comparisons of the FR oscillator were continued with a standard chronometer developed in the gravimetric laboratories TsNIIGAiK, under the supervision of L.A. GERENBURG (32). These chronometers in their turn were checked against reception of time-signals from the ether.

The standard chronometers were characterized by high stability of rate ($1-2 \times 10^{-8}$ s), and the rate was checked by means of accurate time-signals with errors significantly better than this stability. As shown by the analysis of the data, a better method of checking the rates of the standard chronometers was by a systematic comparison between themselves at the stations, and by the calibrated frequency at the base station. A graph of the daily variation of the two standard chronometers is shown in Fig. 3.

An important feature of the observations with OVM is the high accuracy of determination of the periods, guaranteeing (in the absence of interferences from microseisms, vibrations etc.) the possibility of determination of the period with errors not exceeding $1 \times 10^{-8}$ sec over 15 min. However, the effect of these interferences, as well as errors depending on small defects in the operation of the arresting device, make it necessary to extend observations to an interval of time of about 10 hours.

## III. Program and method of experimental work (1965)

After the laboratory investigation of the equipment (1964) it was shown to be possible to begin observations at stations (called B, C, and D), determined earlier by the aerogravimetric expedition of the Institute of Physics of the Earth of the Academy of Sciences of USSR. The main objective of the project was working out a method of observation with the new equipment and development of the type of procedure with the equipment for gravimetric connexions.

In 1965 observations were carried out successively at points A, B, A, C, A, D, A, using all three OVM sets, and also using both VMP sets at two of the above points.

Observations with the OVM were conducted according to the following program.

After starting the pendulums, the periods of their oscillations were determined from a series lasting 17 min., i.e. 1024 full oscillations of the pendulums.

After determining the periods from the counting device, without arresting the pendulums, recording was started again for the next 17-min. series, etc. Normally four series with gradually decreasing amplitudes were observed for each start; these series comprised an interval. At the beginning and end of each series the amplitude of the fictitious pendulum, the temperature, and the air pressure inside the apparatus were determined.

On completion of an interval the pendulums were arrested and observed anew with the initial amplitude in accordance with the programmed arrangement. Thus, for each value of the initial amplitude (in the programmed arrangement there are three different initial amplitudes) up to 10-15 intervals are obtained at a station.

In Table 2 a summary of the corrected periods of the pendulums is presented for apparatus No. 2, with initial amplitudes of 47' and 23' (two different programs). The accuracy was evaluated separately for each program. Here $S_1$, $S_2$, $S_3$, and $S_4$ are periods determined from one series of duration about 17 min.; $S_{sr}$ is the average period from four series (an interval), whose observations were carried out with constantly diminishing amplitudes, without arresting the pendulums. In this table, for all periods listed, for example in column $S_1$ ($S_2$, $S_3$, $S_4$, and $S_{sr}$), the average value of the amplitudes is constant.

In the next two columns are listed the mean-square error m for the separate series, obtained from the internal consistency of one interval (column 15), and the mean-square error M for an interval of observations, calculated from the formula

$$M = m/n^{\frac{1}{2}}$$

where n is the number of series in an interval.

Underneath the line, the average values for the corresponding column of measurements are given, and also the calculated mean-square error of one series m' and of an interval $m_1'$ of observations. The latter were obtained from the consistency of the periods in the particular column. Beneath are written the errors of the average periods M' at the station, determined from the formula.

$$M' = m'/n'^{\frac{1}{2}}$$

where n' is the number of intervals. Further, the mean-square error for the whole program $M_1'$ is presented.

With this method of observations, and also the special feature of the starting device of OVM, it was possible to accumulate comprehensive data for characterization of the dependence of the results and the accuracy of the observations on the initial amplitude of oscillation of the pendulums. It was shown that, as in the analogous investigations for the other type of pendulums and apparatus, the theoretical correction for the amplitude did not correct fully the observed periods. In fact the actual dependence of period on amplitude is different for different pendulums.

For calculation of the random errors of measurement of m, M in the second program (initial amplitude 23') this systematic dependence was plotted, starting from the assumption that the period depends linearly on the residual influence of the amplitude.

From Table 2, it follows that for initial amplitude close to 23', the agreement of the measured periods according to rows is significantly less than according to columns. This implies that the error in the period introduced by arresting the pendulums exceeds the other errors (influence of microseisms, vibrations, recording, etc). The average value of the errors being compared are: $m = \pm 2.6 \times 10^{-8}$s, $m' = \pm 4.9 \times 10^{-8}$s (for initial amplitude 23').

For initial amplitude 47', these errors are very much closer ($m = \pm 2.6 \times 10^{-8}s$, while $m' = \pm 3.1 \times 10^{-8}s$). From analysis of the data obtained, an optimal amplitude may be deduced for oscillation of the pendulums for high-accuracy measurements.

Besides the principal observations, for which the mean periods of both pendulums of a pair were determined, for several intervals at each station the periods of the individual pendulums were observed (by the method of Vening-Meinesz).

In 1965, when the operations with VMP were begun, enough data for this had already been collected to draw a conclusion about the possibility of some reduction in the observation interval with use of photo-electronic recording of the periods of oscillation of the pendulums. This conclusion was confirmed already by the data in Table 2, indicating that the accuracy of the results depends on the number of arrests, and not on the number of series in an interval. However, in view of the experimental character of the observations on the OVM it was not reasonable to reduce the number of series for these apparatuses. As regards the VMP, it was possible to use to the full extent the higher accuracy of measurement assured by photo-electronic recording. Therefore the interval of observations consisted of two seventeen-minute series. At each point, as formerly, 20 intervals were observed with this apparatus.

Inasmuch as the VMP was not evacuated, and the photo-electric adapter was not attached directly to the apparatus, it was difficult to maintain a zero error of asymmetry. Therefore the connection was determined and introduced for each series of observations. The following order of observations of separate series was established, in which were determined: the degree of asymmetry, the amplitude of oscillations of the actual pendulum 1, amplitude of oscillations of the actual pendulum 2, amplitude of the fictitious pendulum, period of the fictitious pendulum, amplitude (repeated) of the fictitious pendulum, amplitude of actual pendulum 2, amplitude of actual pendulum 1, degree of asymmetry.

The temperature inside the equipment and the air pressure were read in the middle of each interval. The humidity of the air inside the apparatus was determined by means of a film hygrometer, the indications of which were determined according to the scale of the FP in the initial and final intervals. Checking of the frequency of the generators of FR were carried out in the same order as for the OVM. The periods of both actual pendulums of a pair were determined in the initial and final observations at a station, during which each step for each pendulum was observed for three intervals.

## IV. Results of work carried out in 1965

In Tables 3 and 4 summaries are presented of the conditions of the observations at all stations separately for each apparatus. These tables do not need special explanation. For the evacuated apparatuses, the conditions of the observations are given for each program, with the corresponding measured initial amplitude. From these tables it can be seen that the conditions at all measured stations differed only a little from conditions at the base.

In Table 5 are included the average periods of oscillation of the mean of a pair of pendulums at the stations for three values of the initial amplitude. Also the mean-square errors M and m are presented.

The data in these tables indicate the dependence of the corrected periods on the amplitude, particularly for apparatus No. 1. Further, the agreement of the measurements varies substantially from station to station.

From Table 5, the mean-square errors of the intervals of observations at different stations and with initial amplitudes of 47', 23', and 6.5', are written out separately (Table 6). If we exclude from these the errors of recording and errors due to the influence of microseisms and vibrations, obtained from the deviations of the periods in the separate series from the corresponding averages for the intervals, then the errors calculated in this way may be designated 'errors of arresting'. It was shown that the latter depend essentially on the initial amplitude of oscillation of the pendulums. The measured errors of arresting are plotted as a function of initial amplitude in Fig. 4 which illustrates this graphically. It is at present difficult to give an exhaustive explanation of this discovery; however, there is no doubt that it is connected with the very complex question of the interaction of the forces in the system 'knife-support'. The experiments described were carried out only with agate knives and agate flats. According to the data for all pendulums, and all initial amplitudes close to 47', the error of arresting was shown to be commensurate with the other errors - the influence of microseisms and vibrations, error of recording of the period, etc.

Thus, the error of arresting, apparently, is connected with the energy of the pendulum. The larger its energy, the smaller can be the initial amplitude. Therefore we can suppose that with increased weight of the pendulum the amplitude may be decreased. It is true that under the basic conditions prepared from other data, the magnitude of the optimal initial amplitude is changed. In passing we remark that the further increase in accuracy of the measured period, and reduction in the time of observation, is connected with the study of the action on the pendulum of external factors: microseisms, vibrations, etc.

For presentation of the behaviour of the pendulums of the OVM set, the average periods at the base stations are plotted in Fig. 5. These show a small change in period, smooth enough to enable reliable interpolation to the observation time at a field station. Parabolic interpolation was used, as is generally done, for calculations of the values of gravity. The accuracy of the measurement was evaluated according to the rules set out in (31).

The measured value of the increment in gravity and its mean-square error are presented in Table 7. Observations with apparatus No. 2 using an initial amplitude of 6.5' were not included in the final results, inasmuch as the possibility of systematic errors when using such a small amplitude had not been analysed. For each measured value of the increment of the acceleration of gravity between the base and a measured station, the mean-square error $m_{\Delta g}$ was calculated. The average value $\Delta g_{sr}$ for all of the OVM set, entrained two errors; the first, written in the same row as the average value of the increment, was calculated a priori from the formula:

$$M'_{\Delta g} = 1/3 \sqrt{m'^2_{\Delta g} + m''^2_{\Delta g} + m'''^2_{\Delta g}}$$

where m', m'' and m''' are the errors in the increment obtained with the individual apparatuses.

The second error $M'_{\Delta g}$ was obtained from the departure of the results for the individual apparatuses from the average value at the station. The error $M_{\Delta g}$, as is usual, is always less than $M'_{\Delta g}$; this testifies, on the one hand to the reliability of the estimated behaviour of the pendulums of each apparatus, and on the other hand, to some overstatement of the a priori errors, which always occurs when the method of evaluation of the accuracy described above is used. In the lower part of the table, analoguus data for the VMP set are presented.

Comparing results of measurements with the OVM and VMP, we see that the disagreement between them is less than the respective errors. However, the number of comparisons was too small to enable any conclusions to be drawn. It is clear only that both sets have the same order of accuracy within the limits of the influence of the casual errors.

As an evaluation of the OVM, we determine the mean-square error of $\Delta g$ for a single apparatus, calculating it from the departure of the values obtained by each apparatus at a given station, from the overall average at the station, using the formula.

$$\varepsilon'_{\Delta g} = \sqrt{[v\,v] / (n - k)} = \pm\ 0.22 \text{ mGal},$$

where $n = 9$ is the number of determinations
$k = 3$ is the number of stations.

Since in working with the OVM set, three apparatuses were involved, the mean-square error of the measurement at a station with the OVM set will be

$$E_{\Delta g} = \varepsilon'_{\Delta g} / \sqrt{3} = \pm\ 0.13 \text{ mGal}.$$

In Table 8 the results of pendulum and gravity meter measurements are compared.

Obviously, these comparisons are inadequate to permit a conclusion about the systematic accuracy of the various results.

Investigations of the systematic errors of all types of pendulum and gravity meter apparatus must be continued, but in any case, the OVM set is suitable for carrying out reliable work.

In conclusion I discharge my pleasant duty in expressing thanks to N.S. GUSEV for help in carrying out the project described, to L.I. KRIMOV, V.V. LOKHOV, and V.N. OREKHOV for their active part in preparation of the vacuum pendulum apparatus.

## TABLE 1

| No. of apparatus | Coefficients | |
|---|---|---|
| | Temperature, sec/deg | Barometric, sec/mm Hg |
| 1 | $9{,}0.10^{-8}$ | $7{,}5.10^{-8}$ |
| 2 | $12{,}9.10^{-8}$ | $7{,}5.10^{-8}$ |
| 3 | $40{,}0.10^{-8}$ | $15{,}6.10^{-8}$ |
| VMP | $30{,}0.10^{-8}$ | $14{,}0.10^{-8}$ |

## TABLE 4

| Designation of stations | Date | Number of observations of periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temperature, degrees | Mean V-3/8, mm | Mean 3/8, mm | Mean relative humidity, % | Daily variation, quartz chronometer No.1, s |
|---|---|---|---|---|---|---|---|---|
| Apparatus 5801 | | | | | | | | |
| $A_I$ | 24/X-17/XI | 24 | 65,4 | 35,42 | 743,92 | -2,88 | 17,80 | +0,663 |
| $A_{II}$ | 30/XI-7/XII | 34 | 63,2 | 35,39 | 738,56 | -2,89 | 17,9 | +0,666 |
| Mean | | | 64,3 | 35,40 | 741,24 | -2,88 | 17,8 | +0,664 |
| C | 24/XI-27/XI | 25 | 61,4 | 35,28 | 756,26 | -3,15 | 19,6 | |
| Difference C-A | | | +2,9 | -0,12 | +15,02 | -0,27 | +1,8 | |
| $A_{III}$ | 30/XI-7/XII | 34 | 63,2 | 35,39 | 738,56 | -2,89 | 17,9 | +0,666 |
| $A_{IV}$ | 15/XII-19/XII | 20 | 62,7 | 35,40 | 751,82 | -2,63 | 16,2 | +0,668 |
| Mean | | | 63,0 | 35,40 | 745,19 | -2,76 | 17,0 | +0,667 |
| D | 10/XII-13/XII | 26 | 62,7 | 35,31 | 725,33 | -2,81 | 17,4 | |
| Difference D-A | | | +0,3 | -0,09 | -19,86 | -0,05 | +0,4 | |
| Apparatus 5802 | | | | | | | | |
| $A_1$ | 28/X-16/XI | 41 | 64,6 | 35,44 | 745,12 | -2,78 | 17,1 | +0,663 |
| $A_{III}$ | 30/XI-7/XII | 24 | 62,1 | 35,42 | 741,45 | -2,72 | 16,8 | +0,666 |
| Mean | | | 63,4 | 35,43 | 743,28 | -2,75 | 17,0 | +0,664 |
| C | 23/XI-27/XI | 26 | 63,0 | 35,40 | 756,46 | -2,81 | 17,4 | |
| Difference C-A | | | +0,4 | +0,03 | +13,18 | -0,06 | +0,4 | |
| $A_{III}$ | 30/XI-7/XII | 25 | 62,3 | 35,42 | 741,45 | -2,72 | 16,8 | +0,666 |
| $A_{IV}$ | 15/XII-24/XI | 36 | 62,4 | 35,44 | 745,34 | -2,59 | 16,0 | +0,668 |
| Mean | | | 62,4 | 35,43 | 743,40 | -2,66 | 16,4 | +0,667 |
| D | 10/XII-13/XII | 21 | 63,2 | 35,36 | 727,33 | -2,64 | 16,3 | |
| Difference D-A | | | -0,8 | -0,07 | -16,07 | +0,02 | -0,1 | |

Initial amplitude 47'

TABLE 2

| Date | Civil time | Temperature degrees | Change in temperature during interval, degrees | Pressure initial/final mm Hg | Initial amplitude | Correction $10^{-8}$ sec | | | Period of oscillation of pendulums, sec. | | | | | m, $10^{-8}$ sec | M, $10^{-8}$ sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | for amplitude | for temp. | for tidal force | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_{sr}$ | | |
| 24/XI | 0h42m | +34,94 | +0,27 | 0,3/0,4 | 47'52 | -530 | +1 | -5 | 0,4938 8453 | 8451 | 8453 | 8457 | 8454 | ±2,6 | ±1,3 |
| | 6 38 | 35,28 | +0,37 | 0,3/0,3 | 47 55 | 521 | -4 | -1 | – | 8450 | 8456 | 8452 | – | – | – |
| | 14 25 | 34,83 | +0,40 | 0,3/0,4 | 47 54 | 522 | +2 | -1 | 8455 | 8453 | 8453 | 8457 | 8454 | 2,0 | 1,0 |
| 25/XI | 3 05 | 35,30 | 0,00 | 0,3/0,3 | 47 57 | 532 | -4 | -4 | 8457 | 8457 | 8459 | 8460 | 8458 | 1,5 | 0,8 |
| | 7 35 | 35,20 | 0,00 | 0,3/0,3 | 48 06 | 531 | -3 | -1 | 8451 | 8449 | 8458 | – | – | – | – |
| | 12 56 | 35,32 | +0,03 | 0,3/0,3 | 47 57 | 529 | -4 | -1 | 8454 | 8451 | 8457 | 8455 | 8454 | 2,5 | 1,2 |
| | 19 28 | 35,30 | 0,00 | 0,3/0,3 | 48 09 | 528 | -4 | -2 | 8447 | 8452 | 8451 | 8453 | 8451 | 2,6 | 1,3 |
| 26/XI | 2 35 | 35,14 | +0,08 | 0,3/0,3 | 47 57 | 527 | -2 | -5 | 8452 | 8449 | 8448 | 8450 | 8450 | 1,7 | 0,8 |
| | 8 39 | 35,28 | 0,00 | 0,3/0,4 | 47 51 | 525 | -4 | -1 | 8452 | 8448 | 8449 | 8446 | 8449 | 2,5 | 1,2 |
| | 14 25 | 35,36 | +0,05 | 0,3/0,3 | 47 49 | 524 | -5 | -1 | 8447 | 8448 | 8455 | 8454 | 8451 | 4,1 | 2,0 |
| | 20 05 | 35,25 | +0,20 | 0,3/0,3 | 48 01 | 524 | -3 | -2 | 8454 | 8454 | – | 8458 | – | – | – |
| 27/XI | 2 10 | 35,33 | 0,00 | 0,3/0,4 | 47 54 | 522 | -4 | -5 | 8449 | 8454 | 8456 | 8453 | 8453 | 3,0 | 1,5 |
| | 9 50 | 35,23 | 0,00 | 0,3/0,3 | 47 52 | 524 | -3 | -1 | 8448 | – | 8453 | 8455 | – | – | – |
| | | | | | | | | | | | | | | ±2,6 | ±1,6 |
| Mean | | 35,21 | +0,11 | 0,3/0,3 | 47 57 | 526 | | | 0,4938 8452 | 8451 | 8454 | 8454 | 8453 | ±2,6 | ±3,1 |
| | | | | | | | | | m' ±3,3 | ±2,8 | ±3,5 | ±2,7 | | | |
| | | | | | | | | | m' i | | | | ±2,7 | | |
| | | | | | | | | | M' ±0,9 | ±0,8 | ±1,0 | ±1,1 | | | ±1,0 |
| | | | | | | | | | M' i | | | | ±0,9 | | |

Initial amplitude23'

TABLE 2 (continued)

| Date | Civil time | Temperature degrees | Change in temperature during interval, degrees | Pressure initial/final mm Hg | Initial amplitude | Correction $10^{-8}$ sec | | | Period of oscillation of pendulums, sec. | | | | | m, $10^{-8}$ sec | M, $10^{-8}$ sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | for amplitude | for temp. | for tidal force | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_{sr.}$ | | |
| 24/XI | 2 06 | +35,20 | +0,10 | 0,4/0,4 | 23'05 | -123 | -3 | -5 | 0,4938 8505 | 8499 | 8494 | 8489 | 8497 | ±0,1 | ±0,0 |
| | 7 59 | 35,30 | +0,13 | 0,4/0,4 | 23 02 | 121 | -4 | -1 | 8501 | 8494 | 8494 | - | - | - | - |
| | 17 40 | 34,95 | +0,42 | 0,3/0,4 | 22 46 | 121 | +1 | -1 | 8503 | 8493 | 8495 | 8487 | 8494 | 3,3 | 1,6 |
| 25/XI | 4 30 | 35,36 | -0,03 | 0,4/0,3 | 22 15 | 114 | -5 | -3 | 8500 | 8489 | 8491 | 8479 | 8490 | 3,7 | 1,8 |
| | 10 09 | 35,15 | +0,20 | 0,3/0,3 | 23 16 | 125 | -2 | -1 | 8507 | 8497 | 8489 | 8482 | 8494 | 3,5 | 1,8 |
| | 14 37 | 35,20 | +0,23 | 0,3/0,3 | 23 20 | 126 | -3 | -1 | - | 8484 | 8483 | 8473 | - | - | - |
| | 20 55 | 35,30 | 0,00 | 0,4/0,4 | 23 13 | 124 | -4 | -3 | 8502 | 8493 | 8488 | 8485 | 8492 | 1,5 | 0,8 |
| 26/XI | 4 08 | 35,32 | +0,05 | 0,3/0,4 | 23 42 | 129 | -4 | -4 | 8500 | 8493 | 8489 | 8488 | 8492 | 2,6 | 1,3 |
| | 11 47 | 35,08 | +0,34 | 0,2/0,3 | 23 14 | 125 | -1 | -1 | 8505 | 8499 | 8491 | 8490 | 8496 | 1,6 | 0,8 |
| | 16 15 | 35,38 | 0,00 | 0,4/0,4 | 23 05 | 122 | -5 | -1 | 8497 | 8488 | 8483 | - | - | - | - |
| | 21 30 | 35,33 | 0,00 | 0,3/0,4 | 22 48 | 122 | -4 | -3 | 8491 | 8486 | 8483 | 8479 | 8485 | 2,5 | 1,2 |
| 27/XI | 11 05 | 35,30 | +0,10 | 0,3/0,3 | 23 16 | 123 | -4 | -1 | 8495 | 8489 | 8487 | 8480 | 8488 | 2,0 | 1,0 |
| | | | | | | | | | | | | | | ±2,6 | ±1,3 |
| Mean | | 35,24 | +0,13 | 0,3/0,4 | 23 00 | 123 | | | 0,4938 8501 | 8492 | 8489 | 8484 | 8492 | ±2,6 | |
| | | | | | | | | | m' ±4,8 | ±4,9 | ±4,3 | ±5,5 | | | ±4,9 |
| | | | | | | | | | $m'_i$ | | | | ±3,8 | | |
| | | | | | | | | | M' ±1,4 | ±1,4 | ±1,2 | ±1,7 | | | |
| | | | | | | | | | $M'_i$ | | | | ±1,3 | | ±1,4 |

TABLE 3

| Designation of station | No. of program | Date | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Apparatus No. 1 | | | | | | | | | |
| | | | Initial amplitude 19' | | | | | Initial amplitude 18' | | | | | Initial amplitude 16' | | | | |
| $A_{I}$ | | 22-26/X | 11 | 83 | 34,84 | -0,04 | 1,4 | 14 | 70 | 34,88 | -0,03 | 1,5 | 12 | 61 | 34,85 | -0,04 | 1,4 |
| $A_{II}$ | | 7-10/XI | 12 | 84 | 34,15 | +0,02 | 1,4 | 12 | 72 | 34,16 | +0,01 | 1,2 | 15 | 62 | 34,14 | 0,00 | 1,2 |
| Mean | | | | 84 | 34,50 | -0,01 | 1,4 | | 71 | 34,52 | -0,01 | 1,4 | | 62 | 34,50 | -0,02 | 1,3 |
| B | | 30/X-1/XI | 10 | 83 | 34,34 | 0,00 | 1,2 | 11 | 71 | 34,34 | -0,03 | 1,2 | 11 | 62 | 34,36 | -0,02 | 1,4 |
| Difference B-A | | | | -1 | -0,16 | +0,01 | -0,2 | | 0 | -0,08 | -0,02 | -0,2 | | 0 | -0,14 | 0,00 | +0,1 |
| $A_{II}$ | 1 | 7-10/XI | 12 | 84 | 34,15 | +0,02 | 1,4 | 12 | 72 | 34,16 | +0,01 | 1,2 | 15 | 62 | 34,14 | 0,00 | 1,2 |
| $A_{III}$ | 2 | | 12 | 82 | 34,30 | 0,00 | 1,4 | 15 | 71 | 34,24 | -0,04 | 1,4 | 12 | 61 | 34,26 | 0,00 | 1,4 |
| | | | 10 | 82 | 34,11 | 0,00 | 1,3 | 12 | 70 | 34,08 | 0,00 | 1,4 | 12 | 61 | 34,14 | -0,02 | 1,3 |
| Mean | | | | 82 | 34,20 | 0,00 | 1,4 | | 70 | 34,16 | -0,02 | 1,4 | | 61 | 34,20 | -0,01 | 1,4 |
| C | | 24-27/XI | 13 | 83 | 33,98 | -0,01 | 1,2 | 13 | 70 | 33,98 | 0,00 | 1,2 | 14 | 60 | 33,92 | 0,00 | 1,3 |
| Difference C-A | | | | +1 | -0,22 | -0,01 | -0,2 | | 0 | -0,18 | +0,04 | -0,2 | | -1 | -0,32 | +0,01 | -0,1 |
| $A_{III}$ | | 1-7/XII | 10 | 82 | 34,11 | 0,00 | 1,3 | 12 | 70 | 34,08 | 0,00 | 1,4 | 12 | 61 | 34,14 | -0,02 | 1,3 |
| $A_{IV}$ | | 17-23/XII | 12 | 81 | 33,98 | +0,02 | 1,3 | 11 | 70 | 33,96 | 0,00 | 1,3 | 11 | 60 | 33,95 | -0,01 | 1,3 |
| Mean | | | | 82 | 34,04 | +0,01 | 1,3 | | 70 | 34,07 | 0,00 | 1,4 | | 60 | 34,04 | -0,02 | 1,3 |
| D | | 10-13/XII | 12 | 82 | 34,00 | 0,00 | 1,4 | 12 | 71 | 34,02 | -0,01 | 1,3 | 10 | 61 | 34,02 | -0,01 | 1,4 |
| Difference D-A | | | | 0 | -0,04 | -0,01 | +0,1 | | -1 | -0,05 | -0,01 | -0,1 | | +1 | -0,02 | +0,01 | +0,1 |

TABLE 3 (continued)

| Designation of station | No. of program | Date | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Initial amplitude 47' | | | | | Apparatus No. 2 Initial amplitude 23' | | | | | Initial amplitude 6,5' | | | | |
| $A_1$ | | 19-25/X | 15 | 522 | 34,79 | +0,08 | 0,4 | 16 | 122 | 34,77 | +0,09 | 0,4 | 17 | 11 | 34,78 | +0,11 | 0,4 |
| $A_{II}$ | | 7-12/XI | 13 | 523 | 35,05 | +0,07 | 0,4 | 13 | 123 | 35,05 | +0,09 | 0,4 | 16 | 10 | 35,05 | 0,11 | 0,3 |
| Mean | | | | 525 | 34,92 | +0,07 | 0,4 | | 122 | 34,91 | +0,09 | 0,4 | | 10 | 34,92 | +0,11 | 0,4 |
| B | | | 14 | 522 | 34,99 | +0,04 | 0,4 | 13 | 124 | 34,99 | +0,07 | 0,4 | 11 | 11 | 34,92 | +0,12 | 0,4 |
| Difference B-A | | | | -3 | +0,07 | -0,03 | 0,0 | | +2 | +0,08 | -0,02 | 0,0 | | +1 | 0,00 | +0,01 | 0,0 |
| $A_{II}$ | | 7-12/XI | 13 | 528 | 35,05 | +0,07 | 0,4 | 13 | 123 | 35,05 | +0,09 | 0,4 | 16 | 10 | 35,05 | +0,11 | 0,3 |
| $A_{III}$ | | 1-7/XII | 14 | 521 | 35,14 | +0,04 | 0,3 | 14 | 125 | 35,05 | +0,13 | 0,3 | 14 | 10 | 34,08 | +0,10 | 0,3 |
| Mean | | | | 524 | 35,10 | +0,06 | 0,4 | | 124 | 35,05 | +0,11 | 0,4 | | 10 | 35,06 | +0,10 | 0,3 |
| C | | 23-27/XI | 12 | 526 | 35,21 | +0,11 | 0,3 | 12 | 123 | 35,24 | +0,13 | 0,4 | 12 | 9 | 35,16 | +0,14 | 0,3 |
| Difference C-A | | | | +2 | +0,11 | +0,05 | -0,1 | | -1 | +0,19 | -0,08 | 0,0 | | -1 | +0,10 | +0,04 | 0,0 |
| $A_{III}$ | | 1-7/XII | 14 | 521 | 35,14 | +0,04 | 0,3 | 14 | 125 | 35,05 | +0,13 | 0,3 | 10 | 10 | 35,08 | +0,19 | 0,3 |
| $A_{IV}$ | | 16-23/XII | 11 | 520 | 35,24 | +0,16 | 0,3 | 12 | 122 | 35,38 | +0,08 | 0,3 | 13 | 10 | 35,25 | +0,11 | 0,3 |
| Mean | | | | 520 | 35,19 | +0,10 | 0,3 | | 124 | 35,22 | +0,10 | 0,3 | | 10 | 35,16 | +0,10 | 0,3 |
| C | | 10-13/XII | | 520 | 35,21 | +0,07 | 0,3 | | | | | | 12 | 10 | 35,15 | +0,02 | 0,3 |
| Difference C-A | | | | 0 | +0,02 | -0,03 | 0,0 | | | -0,02 | -0,05 | 0,0 | | 0 | -0,01 | -0,08 | 0,0 |

TABLE 3 (continued)

| Designation of station | No. of program | Date | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg | No. of observed periods | Mean correction for amplitude, $10^{-8}$ sec | Mean temp., degrees | Mean change in temperature over interval, degrees | Mean pressure, mm Hg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Apparatus No. 3 | | | | | | | | | |
| | | | Initial amplitude 32' | | | | | Initial amplitude 28' | | | | | Initial amplitude 22' | | | | |
| $A_I$ | | 23-26/X | 12 | 196 | 35,05 | 0,00 | 0,8 | 12 | 155 | 35,07 | -0,02 | 0,8 | 12 | 91 | 35,07 | -0,01 | 0,8 |
| $A_{II}$ | | 6-14/XI | 16 | 196 | 35,07 | +0,02 | 0,8 | 16 | 155 | 35,12 | +0,01 | 0,9 | 17 | 92 | 35,09 | 0,00 | 1,0 |
| Mean | | | | 196 | 35,06 | +0,01 | 0,8 | | 155 | 35,10 | 0,00 | 0,8 | | 92 | 35,08 | 0,00 | 0,9 |
| B | | 30/X-1/XI | 10 | 196 | 35,14 | -0,02 | 0,8 | | 155 | 35,14 | 0,00 | 0,8 | 9 | 92 | 35,16 | -0,02 | 1,0 |
| Difference B-A | | | | 0 | +0,08 | -0,03 | 0,0 | | 0 | +0,04 | 0,00 | 0,0 | | 0 | +0,08 | -0,02 | +0,1 |
| $A_{II}$ | | -14/XI | 16 | 196 | 35,07 | +0,02 | 0,8 | 16 | 155 | 35,12 | +0,01 | 0,9 | 17 | 92 | 35,09 | 0,00 | 1,0 |
| $A_{III}$ | | 1-7/XII | 12 | 193 | 35,28 | 0,00 | 1,0 | 13 | 156 | 35,23 | +0,01 | 0,8 | 15 | 93 | 35,25 | +0,01 | 0,9 |
| Mean | | | | 194 | 35,18 | +0,01 | 0,8 | | 92 | 35,18 | +0,01 | 0,8 | | 92 | 35,17 | 0,00 | 1,0 |
| C | | 24-27/XI | 13 | 193 | 35,05 | 0,00 | 1,0 | 12 | 155 | 35,07 | -0,02 | 1,0 | 10 | 92 | 35,05 | -0,01 | 0,9 |
| Difference C-A | | | | -1 | -0,13 | -0,01 | -0,1 | | -1 | -0,11 | -0,03 | +0,2 | | 0 | -0,12 | -0,01 | -0,1 |
| $A_{III}$ | | 1-7/XII | 12 | 193 | 35,28 | 0,00 | 1,0 | 13 | 156 | 35,23 | +0,01 | 0,8 | 15 | 93 | 35,25 | +0,01 | 0,9 |
| $A_{IV}$ | | 16-95/XII | 1 | 182 | 35,39 | +0,01 | 0,8 | 12 | 156 | 35,37 | +0,07 | 0,9 | 1 | 92 | 35,74 | +0,09 | 1,0 |
| Mean | | | | 188 | 35,34 | 0,00 | 0,9 | | 156 | 35,30 | +0,08 | 0,8 | | 92 | 35,50 | +0,05 | 1,0 |
| D | | 10-13/XII | 11 | 190 | 35,30 | -0,02 | 0,9 | 12 | 155 | 35,25 | -0,04 | 1,0 | 12 | 92 | 35,28 | +0,01 | 0,9 |
| Difference D-A | | | | +2 | -0,04 | -0,02 | 0,0 | | -1 | -0,02 | -0,12 | +0,2 | | 0 | -0,22 | -0,04 | -0,1 |

TABLE 5

| Designation of section, No. of program | No. of Intervals | Mean period, sec | M, $10^{-8}$ sec | m, $10^{-8}$ sec | No. of Intervals | Mean period, sec | M, $10^{-8}$ sec | m, $10^{8}$ sec | No. of Intervals | Mean period, sec | M, $10^{-8}$ sec | m, $10^{-8}$ sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Apparatus No. 1 | | | | | | | |
| | Initial amplitude 19' | | | | Initial amplitude 18' | | | | Initial amplitude 16' | | | |
| $A_1$ | 11 | 0,4915 5071 | ±2,6 | ±8,7 | 14 | 0,4915 5060 | ±1,8 | ±6,9 | 12 | 0,4915 5055 | ±2,3 | ±8,0 |
| B | 10 | 0,4915 2615 | 2,4 | 7,5 | 11 | 0,4915 2605 | 1,8 | 5,7 | 11 | 0,4915 2598 | 1,8 | 6,2 |
| $A_{II}$ 1 | 12 | 0,4915 5108 | 1,0 | 3,4 | 12 | 0,4915 5098 | 1,5 | 5,2 | 15 | 0,4915 5094 | 1,0 | 3,6 |
| 2 | 12 | 5117 | 1,2 | 4,2 | 15 | 5108 | 1,0 | 3,9 | 12 | 5102 | 1,4 | 4,9 |
| C | 13 | 0,4914 7948 | 1,6 | 5,6 | 13 | 0,4914 7936 | 1,8 | 6,4 | 14 | 0,4914 7931 | 2,8 | 10,3 |
| $A_{III}$ | 10 | 0,4915 5129 | 1,4 | 4,6 | 12 | 0,4915 5118 | 1,6 | 5,5 | 12 | 0,4915 5111 | 1,7 | 5,9 |
| D | 12 | 0,4915 9814 | 1,2 | 4,2 | 12 | 0,4915 9802 | 1,2 | 4,4 | 10 | 0,4915 9794 | 0,8 | 2,5 |
| $A_{IV}$ | 12 | 0,4915 5131 | 2,8 | 9,4 | 11 | 0,4915 5123 | 2,0 | 6,6 | 11 | 0,4915 5119 | 1,4 | 4,6 |
| Mean square | | | ±1,8 | ±6,0 | | | ±1,6 | ±5,6 | | | ±1,6 | ±5,8 |
| | | | | | Apparatus No. 2 | | | | | | | |
| | Initial amplitude 47' | | | | Initial amplitude 23' | | | | Initial amplitude 6',5 | | | |
| $A_1$ | 15 | 0,4939 5628 | ±1,5 | ±4,6 | 16 | 0,4939 5666 | ±2,1 | ±6,2 | 17 | 0,4939 5639 | ±3,4 | 11,9 |
| B | 14 | 0,4939 3148 | 1,7 | 4,8 | 13 | 0,4939 3192 | 1,3 | 3,9 | 11 | 0,4939 3159 | 2,7 | 7,2 |
| $A_{II}$ | 13 | 0,4939 5654 | 1,0 | 3,2 | 13 | 0,4939 5690 | 1,9 | 6,5 | 16 | 0,4939 5661 | 3,3 | 11,8 |
| C | 12 | 0,4938 8453 | 0,9 | 2,7 | 12 | 0,4938 8492 | 1,3 | 3,8 | 12 | 0,4938 8445 | 3,3 | 9,9 |
| $A_{III}$ | 14 | 0,4939 5662 | 1,6 | 5,6 | 14 | 0,4939 5707 | 2,2 | 7,8 | 14 | 0,4939 5662 | 2,2 | 7,8 |
| D | 12 | 0,4940 0364 | 1,4 | 4,1 | 10 | 0,4940 0399 | 1,2 | 4,0 | 12 | 0,4940 0346 | 3,5 | 11,6 |
| $A_{IV}$ | 11 | 0,4939 5657 | 1,3 | 4,0 | 12 | 0,4939 5688 | 7,0 | 7,0 | 13 | 0,4939 5639 | 2,4 | 7,7 |
| Mean square | | | ±1,3 | ±4,2 | | | ± 1,7 | ±5,6 | | | ±3,0 | ±9,7 |
| | | | | | Apparatus No. 3 | | | | | | | |
| | Initial amplitude 32' | | | | Initial amplitude 28' | | | | Initial amplitude 22' | | | |
| $A_1$ | 12 | 0,4918 1615 | ±1,8 | ±6,4 | 12 | 0,4918 1607 | ±1,2 | ±4,2 | 12 | 0,4918 1605 | ±1,2 | ±4,3 |
| B | 10 | 0,4917 9125 | 2,0 | 6,1 | 10 | 0,4917 9124 | 2,4 | 7,2 | 9 | 0,4917 9113 | 1,8 | 5,6 |
| $A_{II}$ | 16 | 0,4918 1604 | 1,2 | 4,8 | 16 | 0,4918 1594 | 1,4 | 5,6 | 17 | 0,4918 1595 | 1,4 | 5,8 |
| C | 13 | 0,4917 4435 | 1,2 | 4,2 | 12 | 0,4917 4425 | 1,2 | 4,4 | 10 | 0,4917 4424 | 1,2 | 3,8 |
| $A_{III}$ | 12 | 0,4918 1598 | 1,6 | 5,5 | 13 | 0,4918 1587 | 1,7 | 6,0 | 15 | 0,4918 1588 | 1,5 | 5,7 |
| D | 11 | 0,4918 0272 | 2,6 | 7,9 | 12 | 0,4918 6265 | 2,2 | 7,8 | 12 | 0,4918 6261 | 2,4 | 7,4 |
| $A_{IV}$ | 1 | 0,4918 1579 | 6,0 | 6,0 | 2 | 0,4918 1569 | 4,3 | 6,1 | 1 | 0,4918 1556 | 6,0 | 6,0 |
| Mean square | | | ±2,3 | ±5,9 | | | ±2,1 | ±5,9 | | | ±2,2 | ±5,5 |

TABLE 5 (Continued)

| Designation of section, No. of program | No. of Intervals | Mean period, sec | M, $10^{-6}$ sec | m, $10^{-8}$ sec | No. of Intervals | Mean period, sec | M, $10^{-6}$ sec | m, $10^{-8}$ sec | No. of Intervals | Mean period, sec | M, $10^{-8}$ sec | m, $10^{-8}$ sec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Apparatus **VMP** | | | | | | | | | | | | |
| Initial amplitude 18' | | | | | | | | | | | | |
| | | No. 5801 | | | | No. 5802 | | | | | | |
| $A_I$ 1 | | | | | 22 | 0,5046 8747 | ±1,4 | ±6,5 | | | | |
| 2 | 25 | 0,5046 8204 | ±1,4 | ±6,8 | 19 | 0,5046 8761 | 1,3 | 5,5 | | | | |
| C 1 | 25 | 0,5046 0830 | 1,9 | 9,5 | 26 | 0,5046 1401 | 0,8 | 4,3 | | | | |
| $A_{II}$ 1 | 14 | 0,5046 8195 | 1,3 | 5,1 | 24 | 0,5046 8756 | 1,1 | 5,6 | | | | |
| A 2 | 20 | 0,5046 8212 | 1,1 | 5,1 | | | | | | | | |
| D | 26 | 0,5047 3020 | 1,1 | 4,9 | 21 | 0,5047 3575 | 1,2 | 5,7 | | | | |
| $A_{IV}$ 1 | 20 | 0,5046 8215 | 1,1 | 4,7 | 20 | 0,5046 8776 | 1,2 | 5,4 | | | | |
| A 2 | | | | | 16 | 0,5046 8768 | 1,4 | 5,5 | | | | |
| Mean square | | | ±1,3 | ±6,0 | | | ±1,2 | ±5,5 | | | | |

TABLE 6

| Station | Initial amplitude in minutes | | |
|---|---|---|---|
| | 47 | 23 | 6,5 |
| | Mean square error of a single series | | |
| A-1 | ±4,6 | ±6,2 | ±11,9 |
| B | 4,8 | 3,9 | 7,2 |
| A-2 | 3,2 | 6,5 | 11,9 |
| C | 2,7 | 3,9 | 9,9 |
| A-3 | 5,6 | 7,8 | 7,8 |
| D | 4,1 | 4,0 | 11,6 |
| A-4 | 4,0 | 7,0 | 7,7 |
| Mean square | ±4,2 | ±5,8 | ±9,9 |
| Error of recording the interval M | ±1,2 | ±1,0 | ±2,3 |
| Arresting error | ±3,8 | ±5,7 | ±9,6 |

TABLE 7

| No. of apparatus | Stations | | | | | |
|---|---|---|---|---|---|---|
| | B | | C | | D | |
| | Measured increment of gravity | | | | | |
| | $\Delta g$ | $m'_{\Delta g}$ | $\Delta g$ | $m'_{\Delta g}$ | $\Delta g$ | $m'_{\Delta g}$ |
| 1 | +99,06 | ±0,22 | +286,87 | ±0,40 | -186,71 | ±0,24 |
| 2 | 99,17 | 0,22 | 286,61 | 0,40 | 186,70 | 0,25 |
| 3 | 99,29 | 0,32 | 286,21 | 0,42 | 186,95 | 0,57 |
| | +99,17 | ±0,15<br>±0,07 | +286,56 | ±0,24<br>±0,19 | -186,79 | ±0,23<br>±0,08 |
| 5801 | | | +286,74 | ±0,47 | -186,95 | ±0,28 |
| 5802 | | | 286,19 | 0,43 | 187,03 | 0,22 |
| | | | +286,46 | ±0,32<br>±0,27 | -186,99 | ±0,18<br>±0,04 |
| Difference in values of OVM and VMP | | | +0,10 | | -0,20 | |
| Overall average | | | +286,52 | ±0,14 | -186,87 | ±0,07 |

TABLE 8

| Designation of station | Measurements | | | Differences | |
|---|---|---|---|---|---|
| | by OVM | by VMP | by gravimeter | 2-4 | 3-4 |
| B | +99,17 | - | +99,51 | -0,34 | - |
| C | +286,56 | +286,46 | +286,36 | +0,20 | +0,10 |
| D | -186,79 | -186,99 | -187,54 | +0,75 | +0,55 |

# Illustrations

Fig. 1. Set of vacuum pendulum equipment:

(1) - vacuum pendulum apparatus;

(2) - photo-electronic recorder;

(3) - control panel;

(4) - vacuum gauge VSB-1;

(5) - vacuum pump VN 461M.

Fig. 2. Pendulums.

Fig. 3. Graphs of change in the rate of quartz chronometers.

Fig. 4. Dependence of the errors of arresting on the initial amplitude of the pendulums.

Fig. 5. Change in the periods of the pendulums during the expedition.

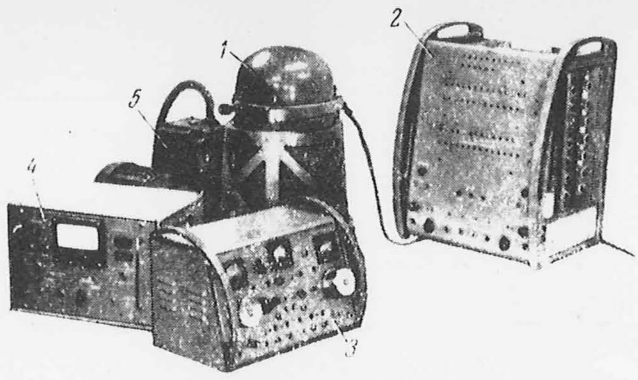


Fig I. SET OF VACUUM PENDULUM EQUIPMENT; I–VACUUM PENDULUM APPARATUS; 2–PHOTO–ELECTRONIC RECORDER; **3**–CONTROL PANEL; 4–VACUUM GAUGE VSB–I; 5–VACUUM PUMP VN 46IM

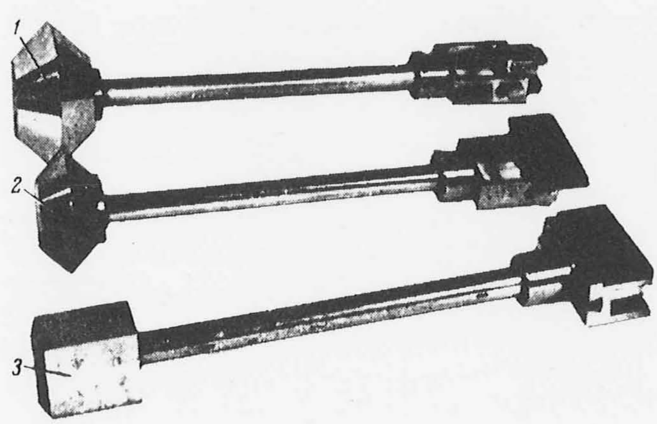


Fig. 2. PENDULUMS

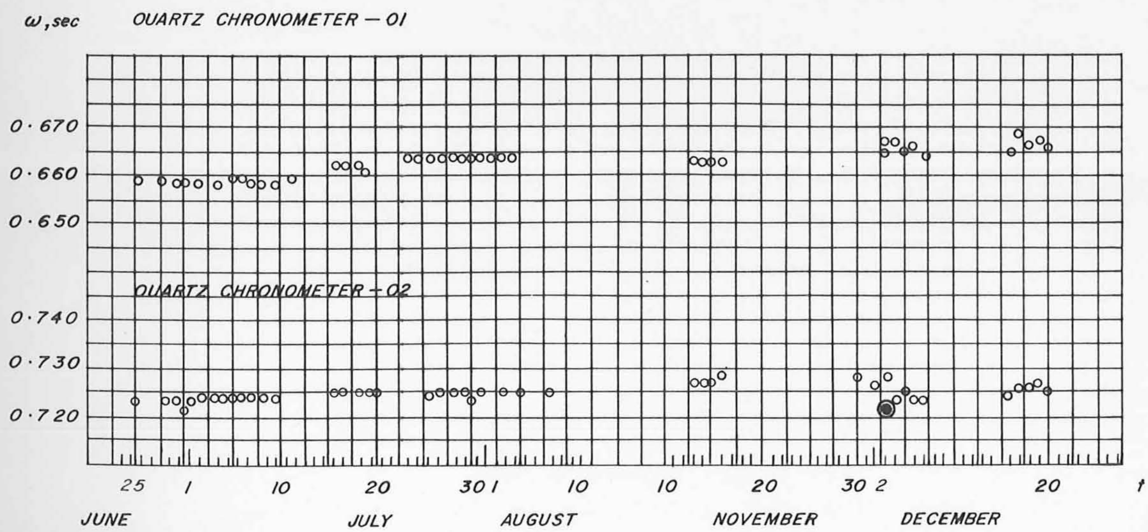


Fig 3 GRAPHS OF CHANGE IN THE RATE OF QUARTZ CHRONOMETERS.

*To Accompany Record No. 1973/119*

G65-356A

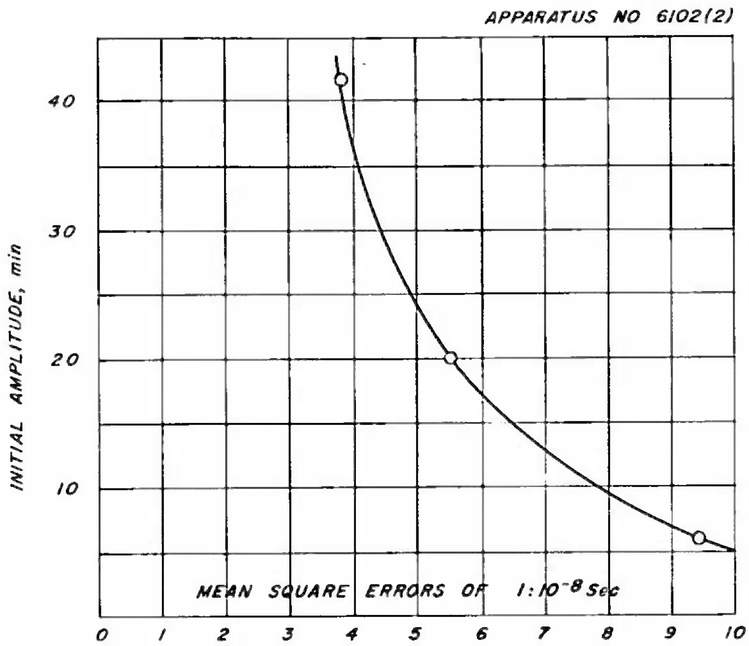


Fig. 4 DEPENDENCE OF THE ERRORS OF ARRESTING ON THE INITIAL AMPLITUDE OF THE PENDULUMS.

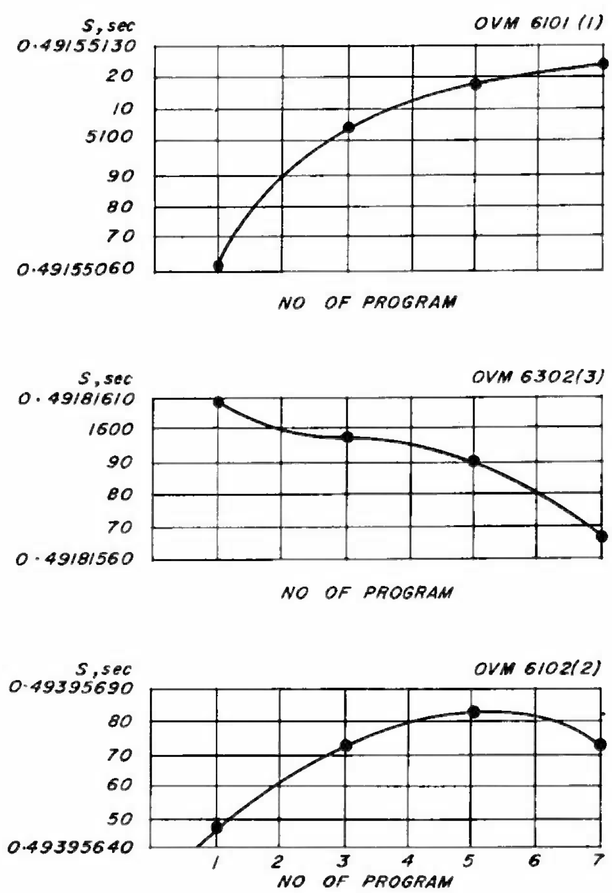


Fig. 5 CHANGE IN THE PERIODS OF THE PENDULUMS DURING THE EXPEDITION.

*To Accompany Record No. 1973/119* G65-358A

# DETERMINATION OF THE PERIOD OF OSCILLATION OF A PENDULUM WITH THE AID OF A CATHODE-RAY TUBE WITH RADIALLY-DEFLECTING ELECTRODES

M.G. Kogan and Yu. A. Slivin

## SUMMARY

A recorder of the period of pendulum oscillations is described, operating with the use of a cathode-ray tube (CRT), and consisting of three blocks: a shaper of the impulse from the pendulums, a curved scanning generator, and a power supply. Impulses from the pendulum are recorded on CRT 8LO30 with radially deflecting electrodes. According to laboratory tests the recorder is quite capable of determining periods with an accuracy of $1.10^{-8}$ sec. The proposed recorder is significantly more reliable than the recorder with an electronic counting unit. The recorder enables 'tying' to a group of readings when 'opening' and 'closing' a series of observations; this gives essentially improved accuracy of the measurements.

The need for visual reading of the screen of the CRT is a disadvantage of operations with the recorder.

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