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EXPERIMENT WITH PARACONIC PENDULUMS DURING THE NOVEMBER 3, 1994 SOLAR ECLIPSE IN BRAZIL

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The present article is the concluding article in a series discussing the results of the author's experiments with paraconic pendulums during solar eclipses from 1990 to 1994. During an eclipse, it is found that the rate of rotation of the pendulum's plane of oscillation increases in the same direction as the Foucault effect by a magnitude equal to that of the Foucault effect. However, all abnormal effects in the behavior of instruments during an eclipse are found to be at the level of instrument and measurement errors and computational errors.

Analysis of the results of an experiment with a paraconic pendulum during the total solar eclipse of July 11, 1991 in Mexico demonstrates [1] that, first, the instrument must function in the continuous mode at the observation point as long as possible, and, second, that several identical instruments are needed. Thus, in anticipation of the total solar eclipse of November 3, 1994 in southern Brazil, two identical instruments that were of the same type as those that had been used in Mexico in 1991, were manufactured by the division of gravity measurements of the Shternberg State Astronomical Institute.

Site and Equipment. From October 27 to November 10, a joint international expedition, which included scientists from Belgium, Italy, Russia, and France, was lodged at the Federal College of Technical Education (26°12′ S, 52°41′ W, Pato-Branco, state of Parana, Brazil).

The eclipse commmenced on November 3 at 9:36:54 local time and concluded at 12:11:59. The total phase began at 10:48:28 (with the Sun 56° above the horizon) and concluded at 10:51:34 (local time).

The equipment was placed in two isolated laboratories with cement floors. The first compartment was intended for a G-783 relative geodynamic gravimeter, an LC&G-402 Lacoste-Romberg tidal gravimeter, and a Philips two-component static vertical pendulum. Paraconic pendulums supplied with recording units were placed in the second compartment.

Agate cones with hemispheres at their ends were used as the suspensions of the two paraconic pendulums, which were entirely identical in terms of dimension, configuration, and mass (mass 1320 g, length 31 cm). The diameters of the contact hemispheres measured 3 mm in the case of the first pendulum and 4 mm in the case of the second pendulum. Agate slabs were used as the slides. Both pendulums were placed in thermostatically controlled chambers. The system for automatic initiation, stop, and computer-aided data collection and control was the same one used in the observations of the solar eclipse of July 11, 1991 in Mexico.

Observations and Data Collection. In preparing the experiment, both devices were, of course, subjected to laboratory testing with complete run-through of the observation technique. The tests demonstrated that the movement of both pendulums was highly stable, and that the data recording system, a description of which may be found in [2], functioned in stable fashion.

On October 27 the expedition arrived at the observation site. The equipment was taken out, tested, and gotten ready for a continuous, round-the-clock mode of observation. At 9:30 on November 1 local time, the experiment commenced. Both pendulums were started in the north–south meridian plane. Every 2 h 45 min, the pendulums were halted and, 15 min later, restarted in the plane of the same meridian, thus completing a single running cycle. The length of each series was selected so as to encompass the duration of the eclipse, which at the observation site amounted to 2 h 35 min.

Every 15 seconds data on the path of the pendulums' travel was taken down by the recording system and transmitted to the memory of a IBM 386 computer, thus forming a data bank. In the course of the experiment, which concluded November 5 at 20:30, the database consisted of a total of 183,504 files of information. A total of 36 series of continuous, round-the-clock observations was obtained for the first pendulum. The agate cone of the second pendulum experienced a microstrain, and so

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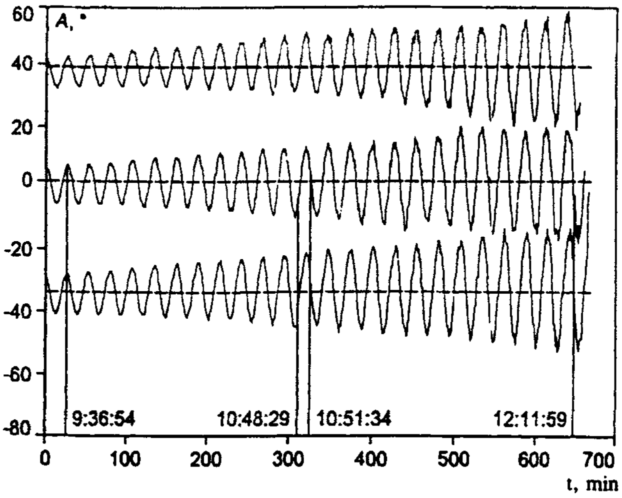

Fig. 1. Azimuth of oscillation plane as a function of time for the first pendulum.

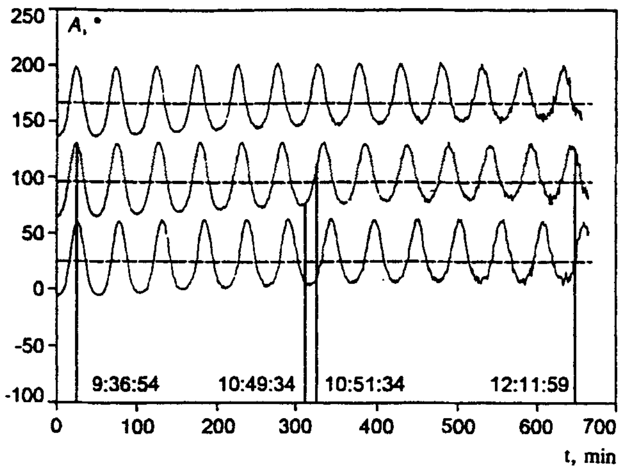

Fig. 2. Azimuth of oscillation plane as a function of time for the second pendulum.

was replaced by a back-up pendulum. Continuous observations of the latter pendulum began November 2 at 21:30. Thus, 24 series of observations were performed with this pendulum. Clearly, there were a total of 60 series performed with the two pendulums, nearly ten times as many as had been performed using the same device on July 10 and 11, 1991 in Mexico (a total of eight series were performed in Mexico).

General Considerations. The obtained data are in the form of coordinates x, y of the elliptical trajectories of the motion of the two pendulums. The azimuths of the major semiaxes of the pendulums' oscillation ellipses were computed using the standard method of least squares. The computation technique and graphical representation of the dependence of azimuth on time was the same as were used in processing the data of the earlier experiment in Mexico [1].

Figure 1 shows comparative graphs representing the dependence of the azimuth of the first pendulum's oscillation plane on time. Three series were taken, first, during the eclipse (middle graph), second, during the 24 h preceding the eclipse (bottom graph), and third, in the course of the 48 h following the eclipse (upper graph); all three series were begun at 9:30 and concluded at 12:15 local time. The horizontal axis expresses time, counted off in min (scale division 2.5 min), and the vertical axis, the azimuth, expressed in degrees (scale division 2°). The digits above the horizontal axis next to the vertical lines denote the starting time of the experiment, the full phase period, and the time at which the eclipse concluded (hour:minute:second), respectively.

In comparing these graphs with the similar graphs for the previous experiment in Mexico (see Fig. 2 in [2]), the following are the principal features that may be noted: (a) the characteristic movement of the pendulum's oscillation plane is

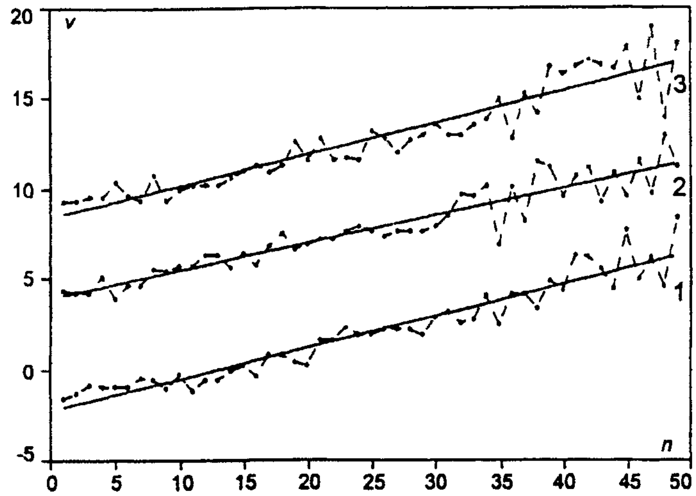

Fig. 3. Variation of rate of rotation of first pendulum's oscillation plane as a function of the length of time it continues to rotate in one direction (period of rotation). *1*) Series of observations in the 24 h prior to the eclipse; *2*) series of observations during the eclipse; *3*) series of observations in the 48 h following the eclipse.

completely preserved, with a periodic reversal in direction, between clockwise and counterclockwise motion, i.e., between rotation in the same direction as the Foucault effect and in the opposite direction; (b) instead of the three periods of 2 h 30 min of the working series that were observed in the experiment in Mexico, here we obtained a total of 49 periods in the course of the 2 h 45 min of the working series. Moreover, even visual comparison of the three graphs leads us to suppose that there are no anomalous discontinuities in azimuth similar to those that were observed with the Allais pendulum during the eclipse in Brazil. It should also be noted that the three graphs are virtually identical. The results of the other 33 series do not differ in any substantial respects from those we have just considered.

Figure 2 presents comparative azimuth-time graphs for the three series with the second pendulum, first, during the eclipse (middle graph), second in the six h preceding the eclipse (bottom graph), and third, in the six h following the eclipse (upper graph). All the notation is the same as in Fig. 1. As in the case of the first pendulum, visual comparison of the graphs makes it clear that the curves are very similar, though there were 25 periods for the working series during the eclipse, and not 49, as in the case of the first pendulum. This is to be expected, since the result is a specific characteristic of each device.

Periodicity. The motion of the first pendulum (device 1) is characterized by a very high degree of stability, both during the entire trial (from October 26 to November 5) as well as during the continuous five-day measurement cycle (from November 1 to 5). In the course of every 2 h, 45 min standard working series of observations, the pendulum's oscillation plane reversed its direction of rotation periodically a total of 49 times. The duration of the individual periods, of course, varied and could differ by as much as 30 sec, though for each series the length of the average period represented an important measure of the stability of the pendulum's motion. (We are not speaking of the pendulum's natural oscillations, but rather the interval of time characterizing the direction of rotary motion of the pendulum's oscillation plane about its vertical axis between the two extreme degenerate position of the oscillation ellipse, at the point at which the pendulum reverses direction [2].) The magnitude of this duration varied only slightly from one series to the next, with a greatest value of 201 sec, and least value of 198 sec. For the mean values of all 36 series, the averaged period $\langle T_{av} \rangle$ = 200 (± 1 sec). For the series of observations made in the course of the eclipse, the length of the average period T_{av} = 200 sec. For the mean values of the 16 series prior to the eclipse, the averaged period $\langle T_{av} \rangle_{pr}$ = 200 (± 1 sec), and for the 19 series following the eclipse, $\langle T_{av} \rangle_{fol}$ = 199 (± 1 sec), respectively. These results show that the range of the average periods of variation of the azimuth of the pendulum's oscillation plane does not exceed not just 3σ, but not even σ.

Unfortunately, after we had been forced to replace the damaged pendulum one day prior to the eclipse by a back-up pendulum, the second device did not prove to be stable. The number of reversals in the direction of motion of the pendulum's oscillation plane varied significantly from one series to the next. In the course of the standard interval of the observation series

(2 h 45 min), it ranged from a minimum of 23 to a maximum of 28. This means that for the observation series, the average period varied from a minimum of 348 sec to a maximum of 412 sec. During the eclipse, the average period of the observation series was equal to 385 sec. Since the averaged period of the mean values for all 24 series $\langle T_{av} \rangle = 367$ (± 15 sec), we see that the variations of the average periods for the second device did not exceed 3σ.

Analysis of Variation of Rate of Rotation of Pendulum's Oscillation Plane. As in our preceding studies [1], the rate of variation of the pendulum's oscillation plane was set equal to the quotient obtained from the division of ΔA_i (variation of azimuth, expressed in min of arc) by T_i (length of time of rotation of the oscillation plane either clockwise or counterclockwise, measured in seconds). Calculations were performed only for the first pendulum, since it exhibited excellent stability.

Figure 3 presents graphs of the variations of the rate of rotation for 49 periods (i.e., 49 changes in the direction of rotation of the pendulum's oscillation plane) during the working series of observations of 2 h 45 min. Here *1* represents the series of observations in the 24 h before the eclipse; *2*, the series of observations during the eclipse; and *3*, the series of observations in the 48 h following the eclipse. The horizontal axis represents the ordinal number of the period n (scale of division 0.5), and the vertical axis the rate of rotation ν in min of arc per second of time (scale of division 0.5′/sec). Thus, this is the same series of observations corresponding to the graphs expressing the variation of the aximuth shown in Fig. 1.

The graphical representation of the rate of rotation in Fig. 3 is approximated by the straight lines. It is quite evident that the trends in the rate of rotation before and after the eclipse are virtually parallel (the same may be said for the other 33 series of observations before and after the eclipse). The trend in the rate of rotation during the eclipse, in contrast, differs substantially from the other trends. The reason for this circumstance is clear from the fact that the graph of the rate of rotation of the pendulum's oscillation plane represents rates of rotation in opposite directions, both in the same direction as the Foucault effect (ν^+) and in the direction opposite to the Foucault effect (ν^-), respectively.

Of the 49 periods (changes in the direction of motion of the oscillation plane), 25 involved motion in the same direction as the Foucault effect, and 24 in the opposite direction. Following summation of the 25 ν^+ and 24 ν^- periods and computation of the average rates of rotation $\langle \nu^+ \rangle$ and $\langle \nu^- \rangle$ for the series of observations during the eclipse (see Fig. 1), it became clear that $\langle \nu^+ \rangle$ was greater than $\langle \nu^- \rangle$. The same result was obtained for all the other 35 series of observations. This means that the pendulum's oscillation plane always rotates more rapidly in the direction of the Foucault effect than in the opposite direction. The mean value of the difference between $\langle \nu^+ \rangle$ and $\langle \nu^- \rangle$ for the 16 series of observations prior to the eclipse was equal to 0.13 ($\pm$0.07′/sec). The mean value of the difference between $\langle \nu^+ \rangle$ and $\langle \nu^- \rangle$ for the 19 series of observations following the eclipse was 0.11 ($\pm$0.07′/sec). The difference for the series of observations during the eclipse is as follows: $\langle \nu^+ \rangle_{ec} - \langle \nu^- \rangle_{ec} =$ 0.30′/sec. Since the mean value of the difference for all 36 series of observations is equal to 0.12 ($\pm$0.07′/sec), it is easily concluded that, during the eclipse, the difference in the rate of rotation in the case of motion in the direction of the Foucault effect versus motion in the opposite direction is beyond 2σ, but within 3σ.

Comparison with Mexican Experiment. As a result of processing the data from the Mexican experiment [1], the variation in the rate of rotation of the pendulum's oscillation plane in the direction of the Foucault effect was obtained. The magnitude of this variation was found to be equal to 0.5′/sec, i.e., five times greater than the Foucault effect for the latitude of Mexico City. However, the size of the sample of control data is, unfortunately, entirely inadequate. The difference in the rate of rotation of the oscillation plane in the direction of the Foucault effect and in the opposite direction during the eclipse is comparable only with the averaged value of this difference, obtained from the four series of observations prior to the eclipse, and with the mean difference of one of the series following the eclipse.

The Foucault effect ν_F in the city of Pato-Branco amounted to roughly 0.1′/sec, which just barely exceeds σ of the mean value of the differences between $\langle \nu^+ \rangle$ and $\langle \nu^- \rangle$ for all 36 observational series of the experiment with the highly stable first pendulum. Denoting the constant component of the mean rate of rotation of the pendulum's rotating oscillation plane for the series of observations during the eclipse by ν_{ec} (it is a characteristic of the pendulum construction), we obtain the mean rate of rotation of the plane in the direction of the Foucault effect in the form $\langle \nu^+ \rangle_{ec} = \nu_{ec} + \nu_F$ and in the direction opposite to that of the Foucault effect, as $\langle \nu^- \rangle_{ec} = \nu_{ec} - \nu_F$. Recalling the magnitude of the Foucault effect (see above), we find that $\langle \nu^+ \rangle_{ec} - \langle \nu^- \rangle_{ec} = 0.2'$/sec. From a comparison with the computed difference 0.3′/sec, it is evident that during the eclipse the rate of rotation of the pendulum's oscillation plane changed by a quantity equal to the local Foucault effect, and not five times the magnitude of the latter, as had occurred in the experiment in Mexico. Moreover, recalling that $\delta\nu$ ($\pm\sigma$) does not exceed $\langle \nu^+ \rangle_{ec} - \langle \nu^- \rangle_{ec}$, and that the latter lies within the interval $\pm 3\sigma$, it seems reasonable to establish only the qualitative variation in the rate of rotation of the oscillation plane, since all the figures presented earlier are within the limit of instrument error and of computation error.

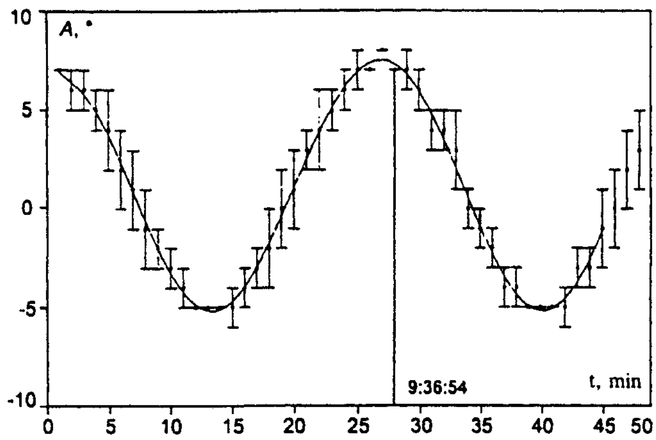

Fig. 4. Azimuth of first pendulum's oscillation plane as a function of time for the series of observations carried out during the eclipse.

Discussion. Based on these experiments in Mexico and Brazil, it is possible to think of the paraconic pendulum as constituting a stable dynamic system. Graphs plotting the azimuth of the major semiaxis of the oscillation ellipse as a function of time for the eight series of observations in Mexico are virtually identical in overall appearance (see Fig. 2 in [1]). Graphs representing these dependences for the pendulums used in the expedition to Brazil are also identical in general appearance for the 36 series with the first pendulum (see Fig. 1) and for the 25 series with the second pendulum (see Fig. 2).

The presence of a constant "noise background" and "singular points" in the pronounced deviation from the basic direction of the graphic curves, so typical of the results of the experiment in Mexico, is not at all confirmed when the data from the observations in Brazil are processed. Nor was any confirmation found for the sharp variation in the magnitude of the azimuth at the start of the eclipse (see Fig. 2 in [1]). In view of the large sample of observations in Brazil and the absence of analogous "singular points" and "noise" during the laboratory trials held in Ferraro (Italy, March-April, 1994) using the two pendulums that were subsequently employed in Brazil, the following hypothesis may be proposed as a potential explanation for this phenomenon in Mexico. The instrument was placed at a depth of 20 m in a laboratory shaft that had been cut out of a lava block. The latter is essentially a resonator of microseisms, the constant presence of which is, in fact, responsible for the "sawtooth" appearance of the curve expressing the dependence of the azimuth of the pendulum's oscillation plane on time (see Fig. 2 in [1]). The "ring" of this lava bell-jar was distinctly recorded by the three-component accelerometer supplied by the French scientists and placed in the adjacent room of the underground laboratory. The response of the laboratory bell-jar to atmospheric shock waves could have been the source of the sharp "recoil" of the azimuth. (That such atmospheric shock waves do, in fact, occur at the start of a solar eclipse may be considered as proven [3].)

To achieve the best possible comparison of the results that were obtained in the experiments in Mexico and Brazil, the system used to record the pendulum's oscillations used in the Mexico-91 experiment was not altered in any way, nor was the software used in computer processing of the data [2]. The results demonstrate that the computation precision must be increased. Figure 4 shows, in magnified scale, part of a typical graph of the dependence of the azimuth of the major semiaxis of the first pendulum's oscillation ellipse on time for the series of observations carried out during the eclipse wtih errors $\pm\sigma_i$ (i = 1, 2, ..., 660). The horizontal axis represents time, plotted in minutes (scale of division 7.5 sec), and the vertical axis, the azimuth in degrees (scale of division 0.5°). The digits above the horizontal axis next to the vertical line denote the start of the eclipse (expressed in the form hour:minute:second). From the graph, it is clear that, in many instances, it was quite difficult to establish the precise moment when the oscillation plane reversed direction, that is, the period of the pendulum's motion in the direction of the Foucault effect versus the period in the direction opposite to the Foucault effect.

There are two ways of increasing the precision of the results, either experimentally, by reducing the measurement error through reducing the noise of the electric currents in the optoelectronic element and increasing the time spent building up the electric charges, or computationally, by creating a complex, high-precision mathematical program for calculating the azimuth of the major semiaxis of the oscillation ellipse on the basis of measured and fixed points in the latter's trajectory. A curve representing an approximation of the aximuth-time dependence by means of a polynomial of degree 10 is presented in Fig. 4.

Approximation of this dependence by means of a polynomial of higher powers would also help in arriving at a more precise value of the moment when the pendulum's oscillation plane reverses direction. But this is a task for the future.

Conclusions. Thus, an increase in the rate of rotation of the pendulum's oscillation plane in the direction of the Foucault effect was observed in the Brazilia-94 experiment, just as had been observed in the Mexico-91 experiment, though its magnitude was only one-fifth that of the latter experiment. The increase in the period of motion of the pendulum's oscillation plane that had been observed during the eclipse in Mexico was not confirmed in the Brazilia-94 experiment. It would appear that if the Mexico-91 experiment had lasted as long as the Brazilia-94 experiment, it could have produced the same result as the latter. It may be suggested that the effect found in the Mexico-91 experiment is a purely instrument effect, since the Brazilia-94 experiment was carried out significantly more carefully and significantly more precisely, and all the anomalous effects were at the level of errors.

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