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ARTICLES

FEATURES AND NOTES

JUST HOW GOOD WAS THE SHORTT CLOCK?

by Pierre H. Boucheron (VA)

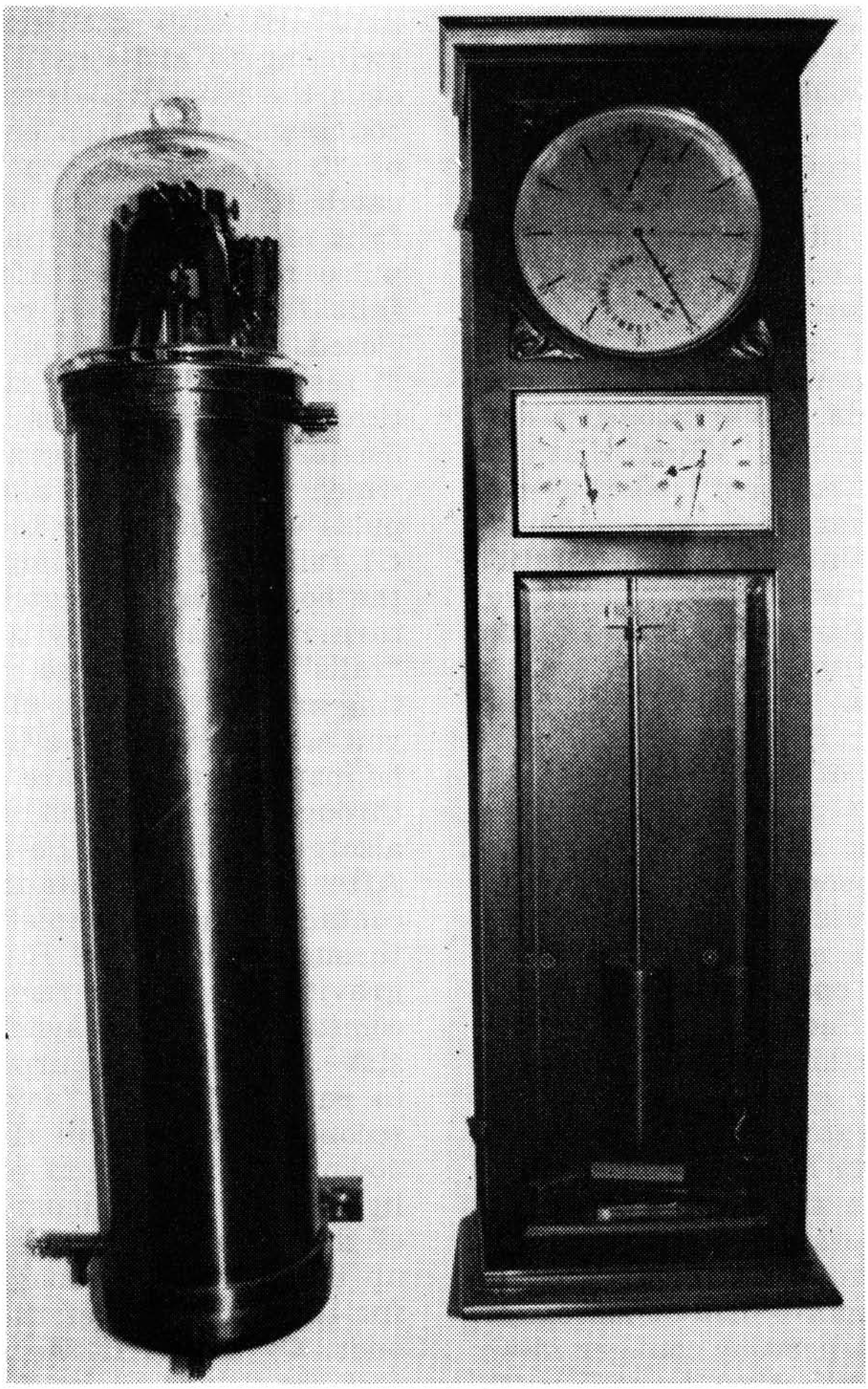

Fig. 1 Shortt Number 48 Master & slave. U.S. Naval Observatory.

Usually the first question which arises is something like: "OK, I've heard of tall case clocks, but what in the world is a short clock?" Alternatively seeing the word in print, the question is "who was Shortt?" William H. Shortt was a British civil engineer who, about 1917, turned his talents to horology, and by 1921 developed an electrically operated free pendulum clock which was destined to dominate the world of precision time keeping well into the 1940's. Astronomers had used pendulum clocks as time standards for nearly three centuries and during that era they rightfully blamed most of the inconsistancies in their observations on the clocks. The advent of the Shortt clock changed all that. Its rate was stable enought to permit, for the first time, accurate observations of earth's nutation. Nutation is the small wobbling motion of the earth's axis which is superimposed on its steady precessional movement. There are many records of Shortt clocks keeping time within one second a year, that is one part in 31 million, far better than most quartz crystal clocks.[1,2] They are also credited with a rate which remains constant within two milliseconds (0.002 second) a day. Of course we now know that the earth's rate of rotation isn't that constant. And what were we comparing the Shortt against? Why the rotation of the earth, what else was there? But that is getting way ahead of the story; you still want to know what a Shortt clock is.

The Shortt free pendulum clock really consists of two pendulums. The free or master pendulum, does absolutely no work at all, while the second, or slave pendulum, counts out 30-second intervals to send electrical signals to the master's drive mechanism and to operate the dial work. A picture of Shortt Number 48 and its slave, on exhibit in the Time Services Building of the United States Naval Observatory in Washington, DC, is shown in Figure 1. The master pendulum is in the large cylinder at the left. In operation the pressure inside the cylinder is held at 20 mm Hg (a little less than 1 inch of mercury). This is done to prevent changes in air pressure from affecting the rate of the pendulum and to minimize losses due to air friction. As is so often the case in this fascinating field of horology, the answer to one question only leads to another and then another. If the master does no work at all, then how does it tell time? The answer is that it doesn't tell time, it merely synchronizes the operation of the slave. Synchronization is accomplished by a beautifully complicated sequence of events which could serve as inspiration to Rube Goldberg the creative cartoon genius of the 1930's.

The sequence of operations is best explained by referring to the electrical/mechanical diagram of Figure 2. Start with the slave pendulum swinging to and fro. Every two seconds the pawl B indexes the 15-tooth count wheel one step until at the end of 30 seconds the trip lever D trips catch K. The gravity impulse arm G falls on cam J imparting a drive impulse to the slave. After the roller falls free of cam J, contacts A are closed. Current flowing through coil M resets G. The same current flowing through coil E releases a catch on the master pendulum's gravity arm G1 which then gently falls on the impulse wheel R'. After the gravity arm G1 falls free of the impulse wheel R' the hook T trips a catch K' which in turn releases gravity arm G2 which "falls" in a clockwise rotation resetting arm G1 by means of roller S. Now you can see why Rube Goldberg would be inspired, and we are only half way through the operation. Reset arm G2 also gently resets G1's holding catch. After G2 completes its travel, it closes contacts which complete the circuit through coils N and H. Coil N resets gravity arm G2 (or remontoire). Now comes the act of synchronizing the slave. The slave is purposely adjusted to run a bit slow (say 1/20th of a second in 30), so coil H pulls a catch down just in time to engage a very light helper spring mounted on the rod of the slave. The helper spring speeds up the slave just enough to make up for the small loss of the past 30 seconds. Of course if the slave is a bit fast the helper spring will have travelled past the catch before it is pulled down and no speed up occurs.

There are a couple of points which are worthy of special attention. First notice that the exact instant of closing of the master's contacts is determined exclusively by the movement of the

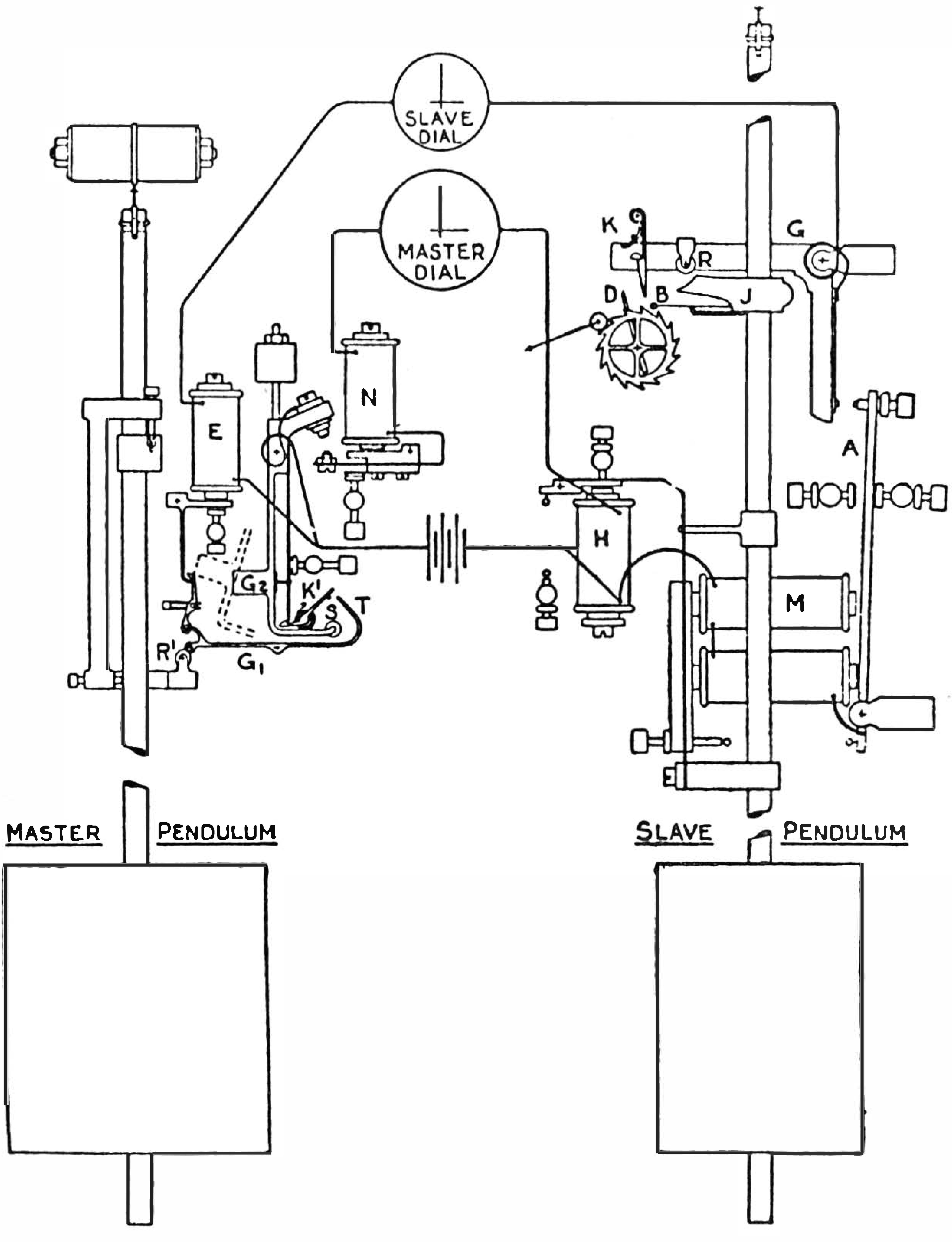

Fig. 2 Electrical/Mechanical diagram of the Shortt clock.

master pendulum, that is — when the impulse arm falls off the impulse wheel plus a slight delay for the reset arm to operate. Next, notice that within reasonable limits variations in the exact time that the slave releases the master's impulse arm will have no effect on the timing of the drive impulse. Effectively there is no chance for a change in what we call "escapement error." Finally, from the complicated description of the interaction between the slave and the master it is pretty evident that starting and running the whole clock is a delicate business subject to every conceivable interaction with Murphy's Law. (Murphy states: If anything can go wrong, it will.) Despite this complexity there are many instances of Shortt clocks operating continuously for many years. Perhaps the longest record is held by Number 11 which operated at Greenwich Observatory from May 1926 until January 1935 when it was stopped to clean a tarnished beat plate!

It is reported that Shortt was never completely content with the performance of his masterpiece. He felt that it should show an even more constant rate than it did. Whether this was the perfectionist nature typical of engineers or whether he suspected something which he couldn't quite put into words, we simply don't know. We do know that there are several things, beyond the obvious temperature and pressure, which can affect a pendulum's rate when we are talking about changes of a few parts in 10 million. For example, the invar rod may have a coefficient of thermal expansion which is almost zero, but when it is green (unaged) it is dimensionally unstable. The elinvar suspension spring is even worse. A most intriguing external effect on the period of a pendulum is that caused by small changes in effective gravity brought about by the gravitational pull of the moon and the sun; in other words, tides.

Rawlings[1] shows a three-year record of the "smoothed" rate of Shortt Number 48 at the Naval Observatory at Washington, DC. In the quest for some basic data on the performance of a Shortt clock, a visit to the Observatory was arranged. The hope was that a detailed examination of the old rate logs of Shortts 38, 41, and 48 might reveal more performance data

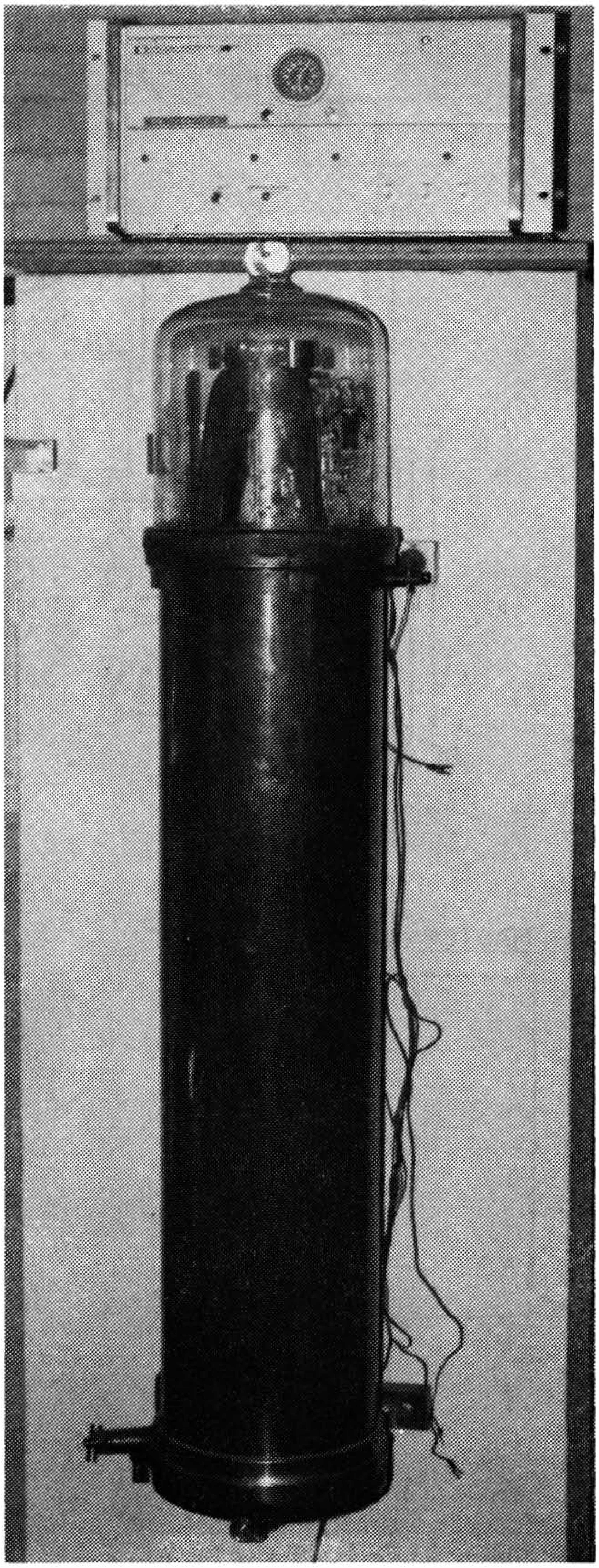

Fig. 3 Shortt Number 41 and cesium atomic clock.

than Rawlings published. Unfortunately this did not prove to be the case. However, while there, we were treated to a private tour of the facility which included a visit to the "new" (1932) North Clock Vault. There, still mounted on its original pier and still holding a vacuum of 20 mm of mercury, was Shortt master pendulum Number 41 (Figure 3). As if to dramatize the inevitable march of progress, a modern cesium atomic clock is rather casually sitting on top of the pier. Close inspection of the pendulum reveals that in some bygone day someone had installed an optically flat window in the side of the bell jar and mounted a first surface mirror at the top of the pendulum's rod. At that point an idea began to form. Without altering the pendulum any more than it already had been, using optics and modern solid state electronics, it might be feasible to put Shortt Number 41 back in service without using the finicky slave pendulum. Furthermore, it would be possible to monitor the performance of the pendulum against the Navy's atomic standards to an accuracy far greater than ever before. After some serious discussions a plan evolved and the Navy graciously agreed to go along with the project with the clear understanding that the results presented here reflect the judgement of the author and not necessarily those of the Naval Observatory. Furthermore, use of the facilities should not be construed to imply any endorsement of the project or its results by the Naval Observatory or the Navy.

Briefly, the scheme which evolved is to project a narrow light beam through the bell jar window, reflect it from the mirror mounted on the pendulum rod, back through the window to a beat plate some 57″ away from the mirror (see Figure 4). At this distance a 1° movement of the pendulum will cause a 2″ movement of the light beam at the

(Continued on next page.)

METALS USED IN HOROLOGY

by Henry Rodgers

BRASS: Brass is an alloy or composition made of different metals such as copper, zinc, lead, and tin. Brass used for watches and clocks must be hard but not brittle. The best composition to produce this and other necessary properties is 66% copper, 33% zinc, and 1% lead. Suitable brass for watch and clockmakers' use should stand hammering to half its original thickness without cracking. When the copper is in excess, zinc being proportionately reduced, the brass becomes soft but tough and will not harden sufficiently. On the other hand, as the proportion of zinc is increased, the brass becomes more brittle and at the same time more fusible. The color changes to a light yellow and, with still more zinc, to greyish white, and brass of this nature is said to be hard. A small percentage of lead is added to make the composition more brittle and less fibrous, just sufficient in quantity to enable the brass to work smoothly while being turned. When tin is added it makes the brass more malleable and softer. Very soft brass chokes the file, and spreads without hardening under the hammer; very hard brass, on the other hand, is fragile, liable to crack when hammered cold, and breaks in passing through the draw plate. Brass is annealed by heating to a dull red in shaded light and plunging into water. If overheated it will disturb the alloys.

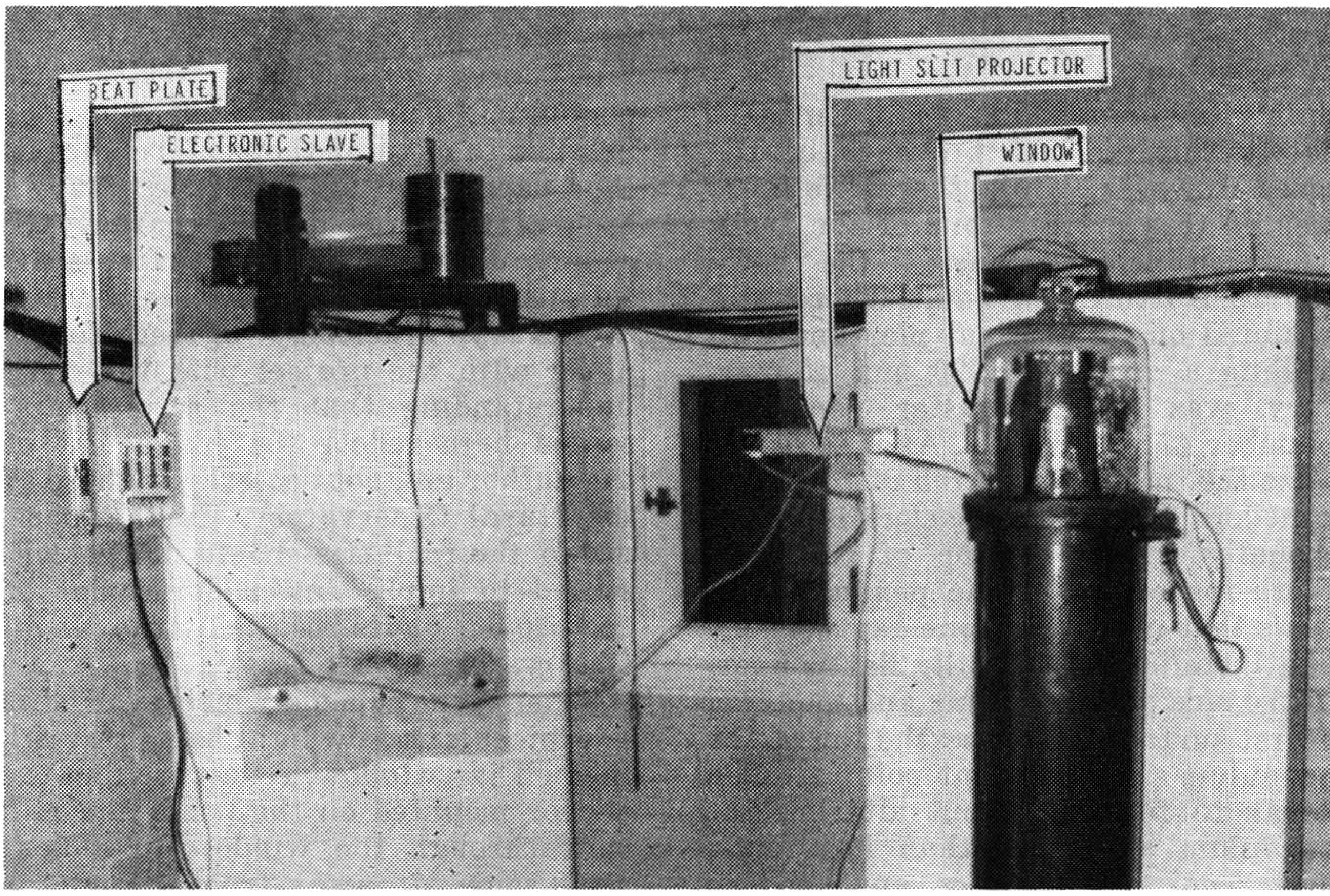

Fig. 4 Shortt Number 41 with electronic slave installed.

beat plate. Next, two photo detectors are mounted on the beat plate. The first is mounted at zero deflection where the pendulum is moving most rapidly and is used to generate the measurement pulse. The second is mounted at 0.75° right deflection and is used to generate the signal which will release the gravity impulse arm of the Shortt drive mechanism. A complete system diagram of the optoelectronic slave pendulum is shown in Figure 5. The system is really quite simple using only 5 integrated circuits and perhaps 6 transistors. The two swing counters, 0-9 and 10-90, simply count the number of pulses generated by photo detector B. A count of 10 AND 20 is sensed by the AND gate and a signal is sent to release the pendulum impulse lever. As the pendulum swings on through its rest position a signal from photo detector A ANDed with the count of 30 resets the swing counters, and that's really all there is to it. Getting the Shortt back in operation, without an instruction book and without the advice of anyone who had ever done it, was something else again. That will be the subject of another paper.

The Observatory maintains several atomic standards of both the cesium beam and hydrogen maser types. Once every hour a computer electronically reads each standard and the readings are averaged to form what is often called a "paper clock." The paper clock has a stability of a few nanoseconds (0.000,000,00x second) per day. Once each hour, generally at one quarter past, the computer also reads the timing from the Shortt clock, compares it with the paper clock and records the difference. No, time from the pendulum clock is not averaged in with the atomic clocks. That would be rather like averaging the speed of a Piper Cub in with the speeds of a fleet of SST's. Since there is always a little jitter, or noise, associated with a reading, the computer actually takes 8 consecutive readings from the pendulum clock. The readings are taken every two seconds to be sure that the pendulum is always approaching the photo detector from the same direction since it is almost impossible to position the detector at dead center and keep it there. Every few weeks the computer is asked to print out the recordings. The 8 samples for each hour are

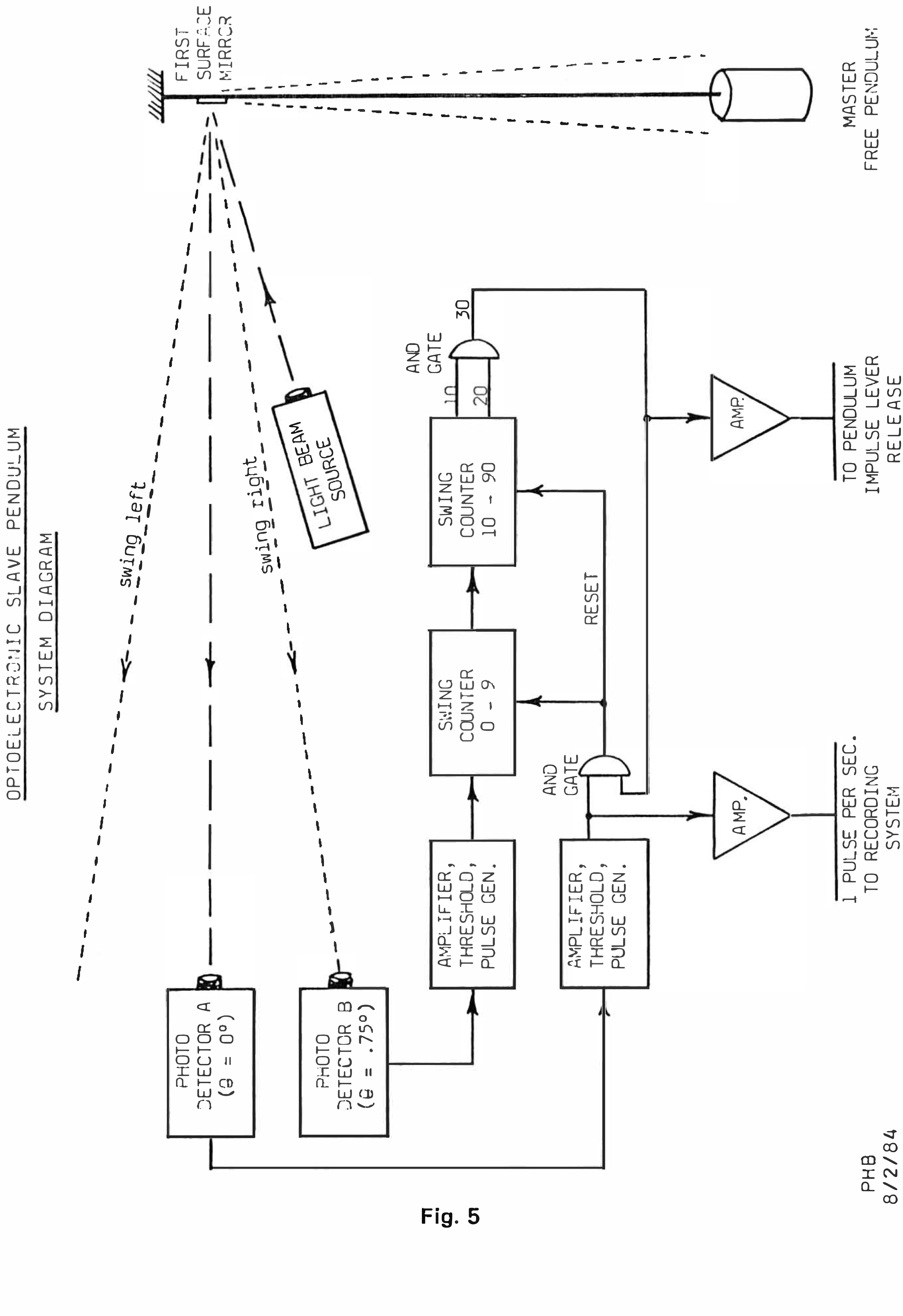
OPTOELECTRONIC SLAVE PENDULUM
SYSTEM DIAGRAM
FIRST SURFACE MIRROR
MASTER FREE PENDULUM
swing left
swing right
LIGHT BEAM SOURCE
AND GATE
30
10
20
SWING COUNTER 10 - 90
SWING COUNTER 0 - 9
RESET
AND GATE
AMP.
TO PENDULUM IMPULSE LEVER RELEASE
AMP.
1 PULSE PER SEC. TO RECORDING SYSTEM
AMPLIFIER, THRESHOLD, PULSE GEN.
AMPLIFIER, THRESHOLD, PULSE GEN.
PHOTO DETECTOR A (θ = 0°)
PHOTO DETECTOR B (θ = .75°)
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Fig. 5

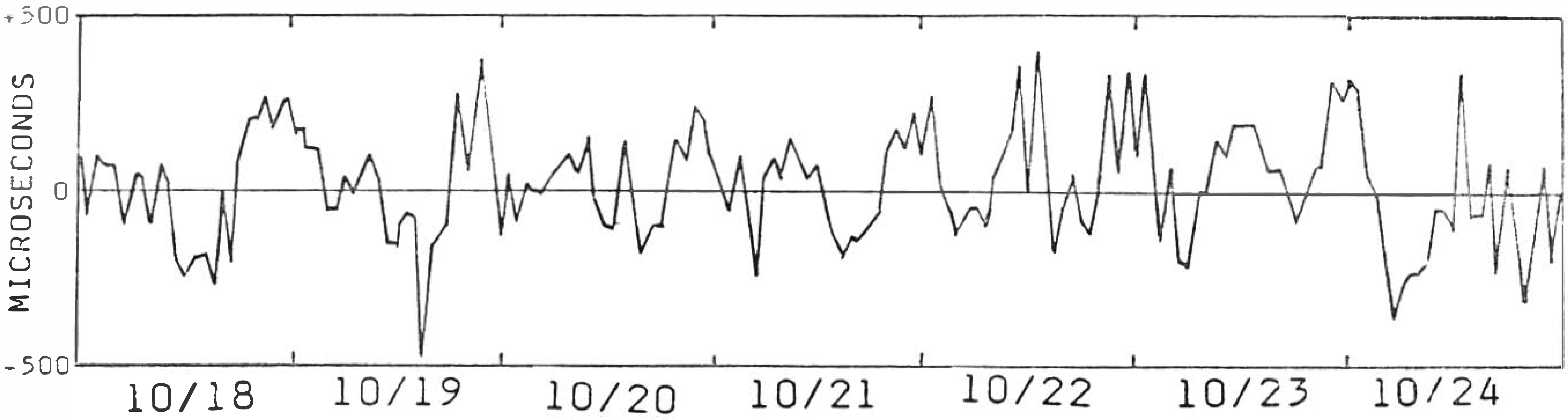

Fig. 6 Hourly rate variation of Shortt Number 41.

averaged together and subtracted from the last hour's average to give the hourly rate. A plot of the hourly rates of Shortt Number 41 for a period of 7 days from October 18 through 24, 1984, is shown in Figure 6. There is nothing special about this period; any other period would look pretty much the same. The clock had been operating for a month when this paper was written and during that period the hourly rate remained pretty much within plus and minus 400 microseconds (0.0004 second). The 24 hourly rates have been averaged together to give the daily rates shown in Figure 7. At least for this first month of operation, clearly the clock's rate remained constant within 200 microseconds per day; ten times better than the 2 milliseconds per day previously reported.[1, 2] Why so much better? There are a number of reasons. First the readings are taken electronically rather than from the mechanical contacts which are always a source of some timing jitter. A very important reason is that the readings are compared against atomic standards thousands of times more stable than the pendulum. Still another reason may be the elimination of a small error in the timing release of the impulse arm due to slight changes in the period of the slave pendulum.

To put the answer to the question "How good was the Shortt clock?" in perspective, if the clock continues to perform as well as it has been it will be keeping time to an accuracy of 1/10th of a second a year. That, of course, is far better than the earth itself does in maintaining its period of rotation. Putting it another way, 200 microseconds a day, or 0.1 second a year is about 2 or 3 parts in 1,000,000,000, which is quite comparable with the very finest of laboratory grade quartz crystal clocks. Fantastic as this may seem, it still isn't the whole answer.

As you may recall from high school physics, the period of a pendulum is directly proportional to the square root of its length divided by the force of gravity. That's fine, but when we are dealing with the sort of accuracies which the Shortt clock is demonstrating, the force of gravity is not all that constant. It turns out that there are a number of earth tides ranging in period from 11.97 hours to 18.6 years.[3] These tides are principally caused by the gravitational attraction of the

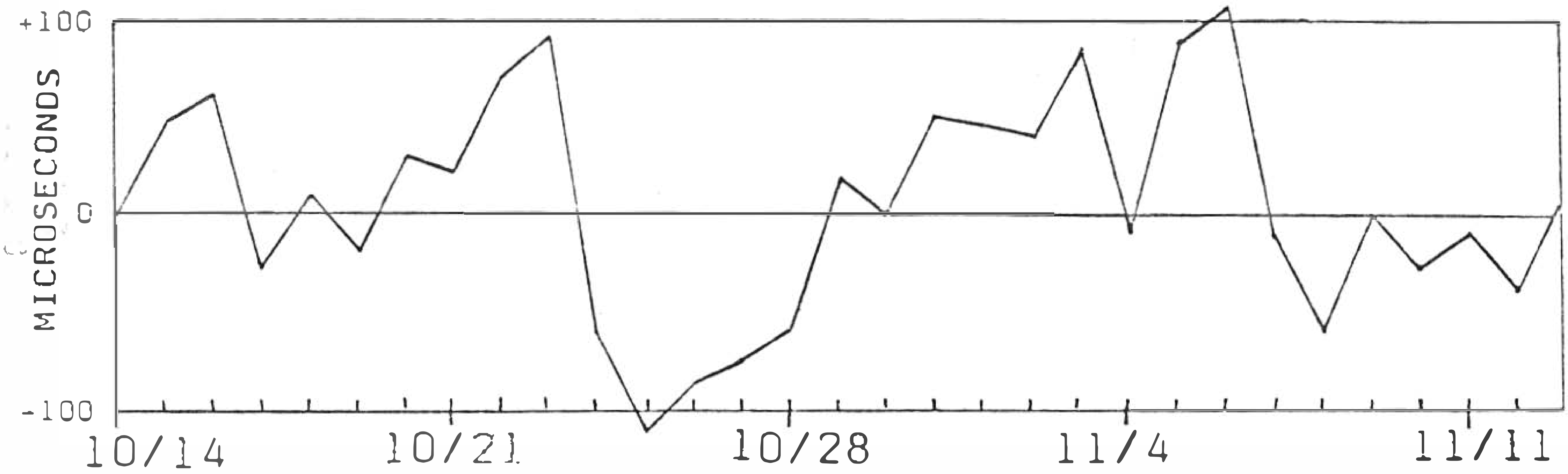

Fig. 7 Daily rate variation of Shortt Number 41.

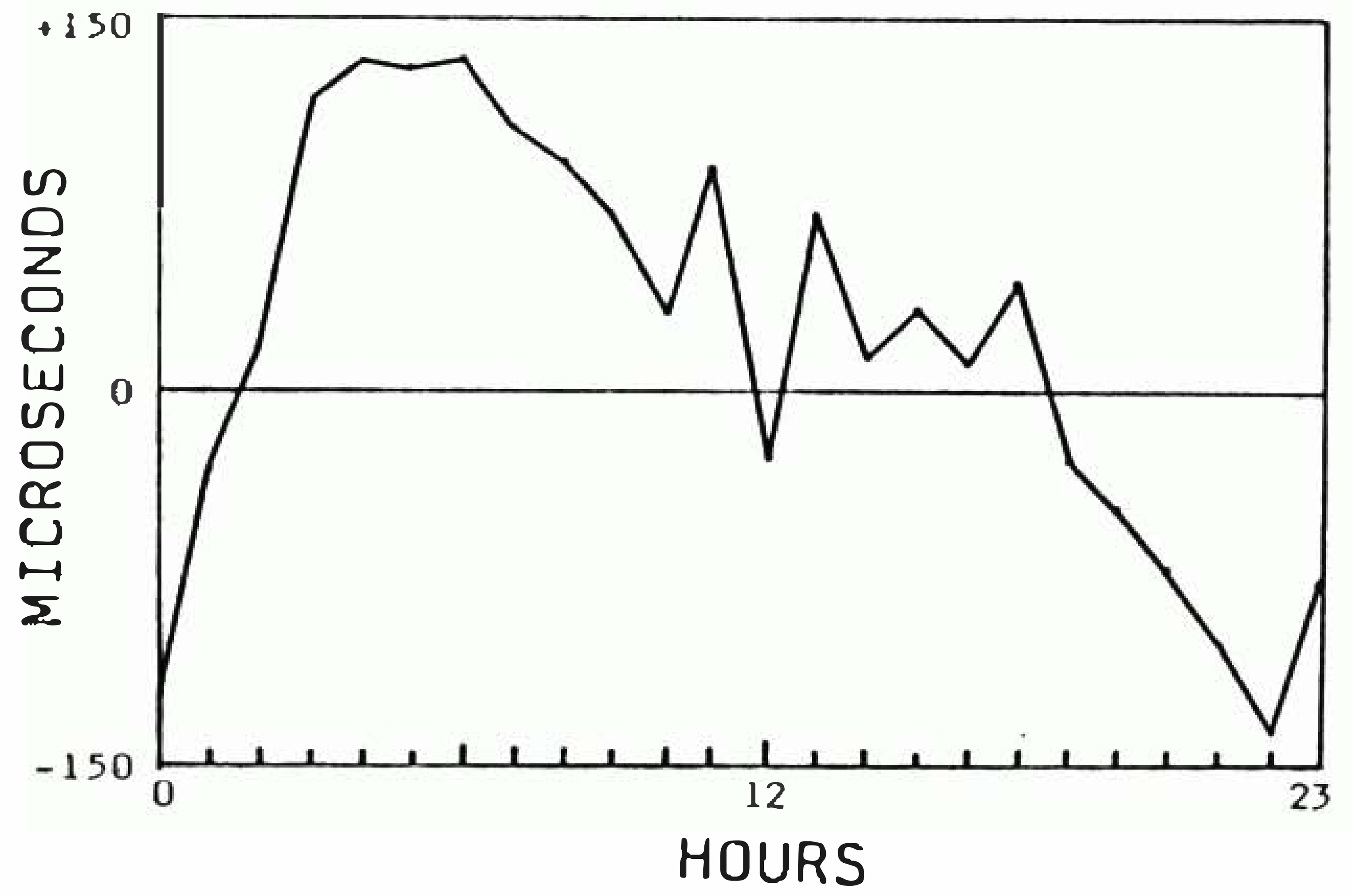

Fig. 8 Shortt Number 41 diurnal rate change.

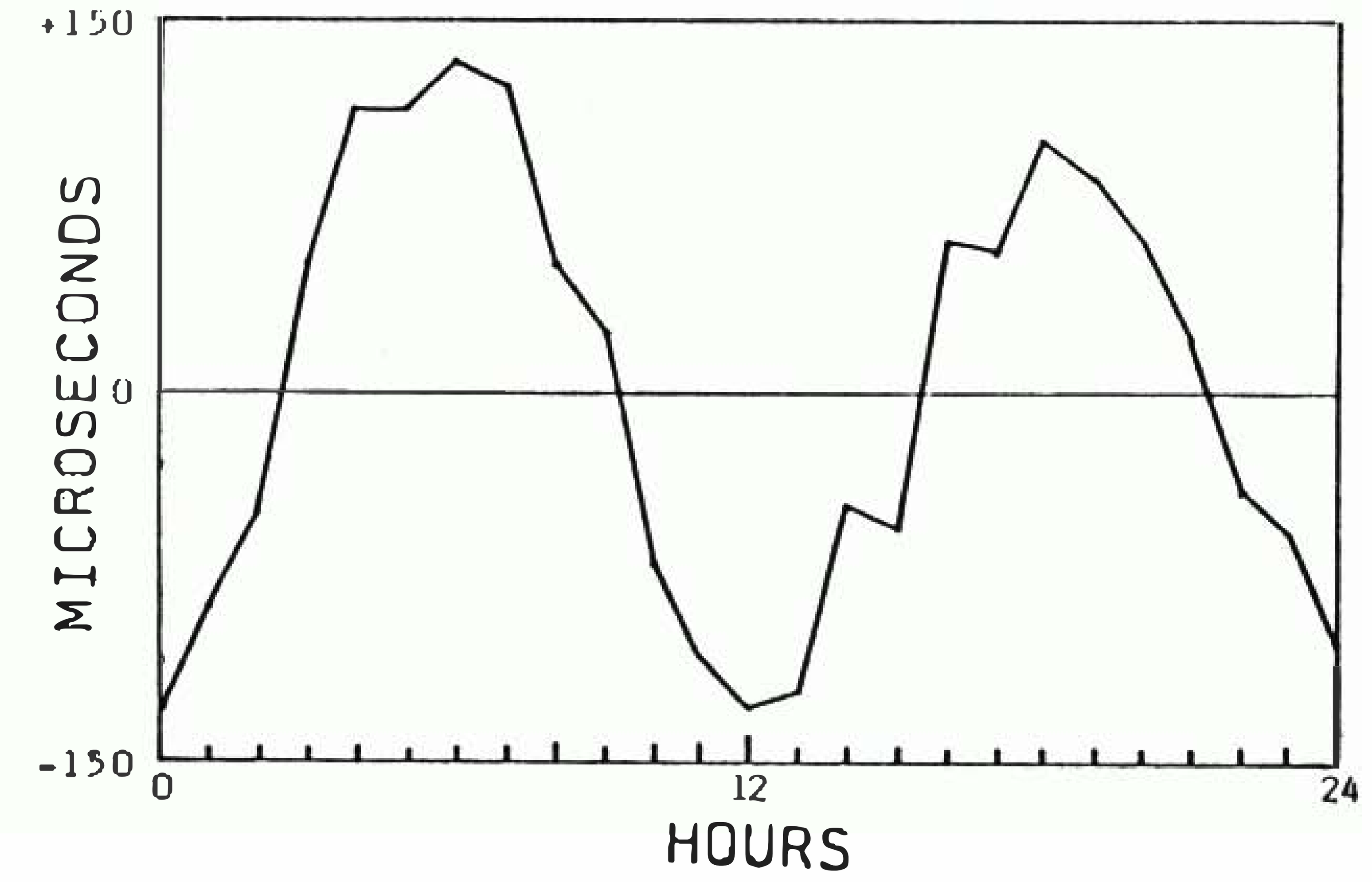

Fig. 9 Shortt Number 41 lunar cycle rate change.

moon and the sun. It is quite beyond the scope of this discussion to go into the subject of earth tides; suffice it to say that a couple of the major cyclic influences will cause changes in effective gravity which will result in changing the pendulum's period by as much as 200 to 300 microseconds a day.

Referring again to the hourly rate chart of Figure 6, even to the practiced eye the variations look pretty much like random noise, but believe it or not there are some periodic functions buried in that data. In order to see the effect of these tides on the period of the pendulum, the same technique which Brown and Brouwer[4] used was applied to the two most dominant: a diurnal sun tide with a period of approximately 24 hours and the stronger and more familiar semi-diurnal moon tide with a period of 12.42 hours. For the 24-hour sun tide the technique is really very straightforward; one simply adds together each day's hourly rate for hour 0 and then divides by the number of days. The same averaging is done for hour 1, 2, 3 . . . 23, and the results are plotted as shown in Figure 8. Noise, being random, will not add to produce a pattern such as this, furthermore if enough days are added together the raggedness of the curve will smooth out. Obtaining the lunar tide shown in Figure 9 is just a little more complicated. First one must predict the hour of moonrise for each day then all the hourly rate data must be skewed so the moonrise always occurs at hour 0 in the averaging process. This isn't anywhere near as difficult as it appears.

The curves shown in Figures 8 and 9 are really quite dramatic. They show an effect which only amounts to a change in timekeeping of plus and minus about 100 microseconds during a day. William H. Shortt was right when he thought that the performance of his clock should be better than it appeared to be. The performance is good enough to see the gravitational attractions of the moon and the sun.

ACKNOWLEDGEMENTS

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Mr. Richard E. Keating, Astronomer, for his enthusiastic support of the project and for many creative ideas.

Mr. Laurance M. Leeds for his recommendations on cleaning and lubricating the mechanism (don't oil it).

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