Fedchenko: Clock or Gravimeter? (Tides, part 5)

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In this series of articles about pendulum clocks, gravity and tides there is one more precision pendulum clock to discuss before the final chapter on the Littlemore clock. In 1958, Feodosii Mikhailovich Fedchenko created Astronomical pendulum clock, model AChF-3. These are accurate to a few ppb (parts per billion) and often regarded as the best pendulum clocks ever made.

A superb and detailed technical description of the F. M. Fedchenko clock was given by Dr. George Feinstein in the April 1995 issue of the NAWCC Bulletin. Derek Roberts also included the same report as chapter 14 of his comprehensive Precision Pendulum Clocks book series.

Background

There are several Fedchenko clock photos on the web. From either the outside or the inside the clock is less impressive looking than the classic, complex, almost artistic mechanical or electro-mechanical pendulum clocks from past centuries. It is a model of simplicity:



Like other clocks in its class, the features of the AChF-3 are that it runs in vacuum (5 mm Hg), has a 1 meter, 10 mm invar rod, small amplitude (100 arc-minutes), and a 10 kg temperature compensated copper bob with thermally exposed core. Two unique features are the isochronous triple spring suspension and electro-magnetic, transistor amplified sense/impulse coils, which are active once every period. This is all covered in great detail in Feinstein's paper.

I should point out that Fedchenko is still a traditional, "free" pendulum clock: no quartz timing is present, no digital electronics is used, and no slave clock is required for impulse timing. It appears simpler in design and fabrication compared to a Shortt.

Search for raw data

My interest with the Fedchenko pendulum clock is its extreme timekeeping performance and its use as a gravimeter. We are fortunate to have high-resolution, year-long, raw data for a Shortt clock, and for the

Littlemore clock, as well as numerous modern one-off amateur precision pendulum clocks. But so far I have been unable to obtain any raw rate- or time-series data for a Fedchenko clock. Given raw data one can make plots of many types, easily compare different clocks, perform mathematical and statistical analysis, and correlate timekeeping performance with changes in environment, including the effect of tides.

Comparison issues

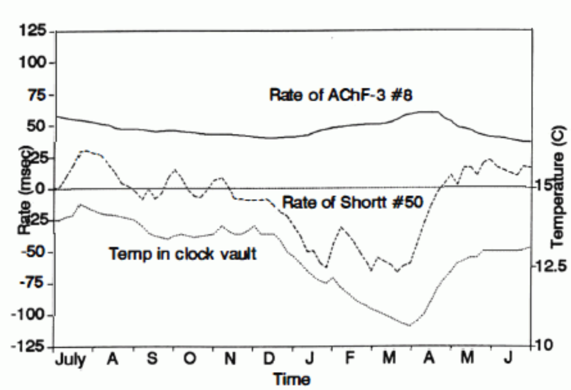
We often talk about Riefler, Leroy, Shortt, and Fedchenko as if they were single clocks that can be compared against one another. I'm told about 100 Shortt-Synchronome clocks were made and perhaps 30 Fedchenko model AChF-3. From what I've seen in the literature the performance of Shortt #x and Shortt #y can easily differ by a factor of ten. When individual serial numbers of the same model differ by this much it is hard to make solid claims that one manufacturer is inherently better than another. In addition, the performance of a given clock may differ significantly depending on age, condition, maintenance and where or how it is installed. For example, one would expect a pendulum clock in a rock solid subterranean chamber to perform better than the same pendulum clock hung on a wall of a museum. Thus, one must be careful comparing *a* Shortt with *a* Fedchenko with *the* Littlemore.

This problem is not unique to pendulum clocks. Laboratory-grade quartz oscillators, even by the same manufacturer and with the same part number, can also exhibit a wide spread in performance. This is the nature of hand-made timekeepers. Quartz crystals are macroscopic objects, the combination of imperfect natural materials and automatic and manual manufacturing processes. This is one reason why those of us interested in the very best quartz oscillators acquire many of them, compare them amongst themselves over time, and then choose the best of the lot for use as phase or frequency standards.

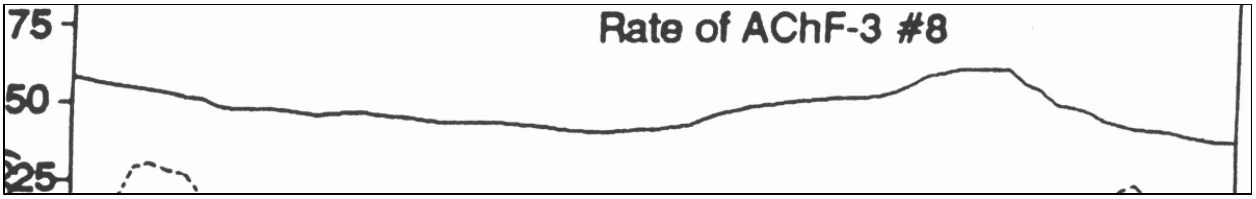
Decoding a rate plot (long-term stability)

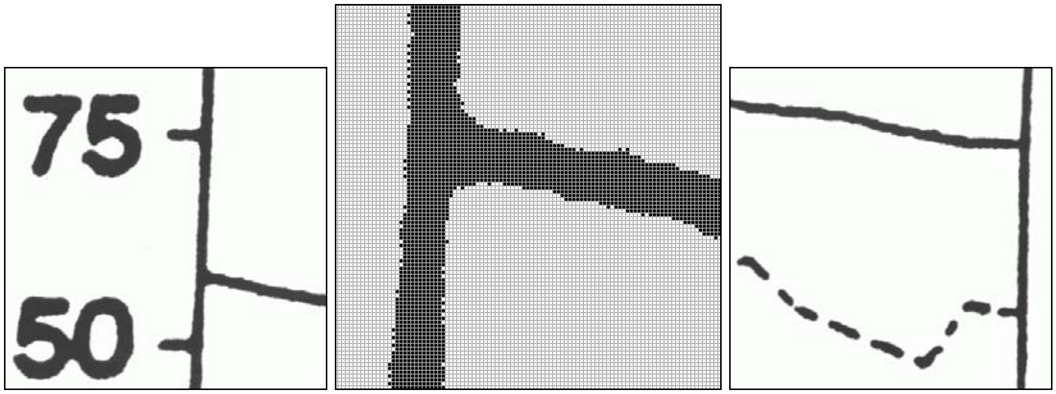
Lacking raw data for a Fedchenko, I looked at the several rate charts reproduced in the Fedchenko articles. One of the plots (figure 24) in the Feinstein paper is shown below. This Fedchenko ran for a total of ten years; the plot below shows one year of operation (from July 1962):

Above, Figure 24. Operation of the impulse mechanism of the AChF-3 clock. Below, Figure 25. Rate curves for AChF-3 No. 8 and Shortt No. 50, by comparison with quartz clock No. 9.

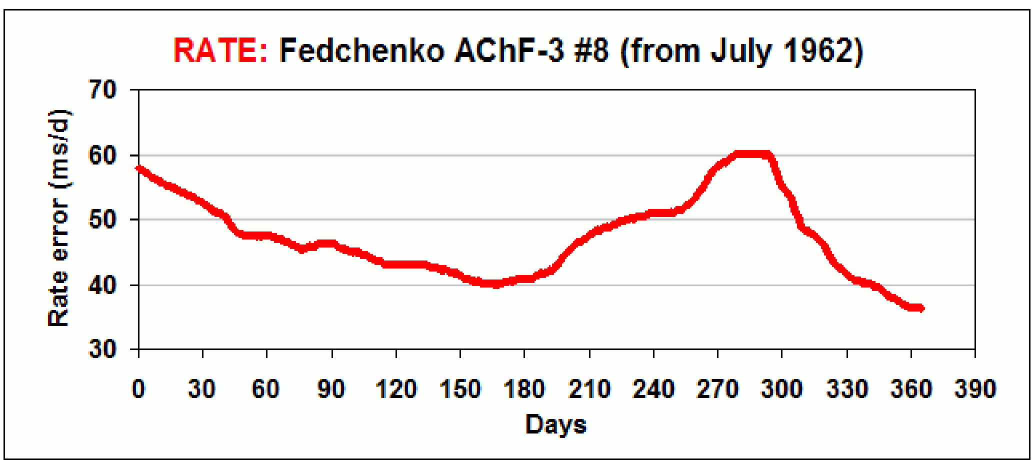


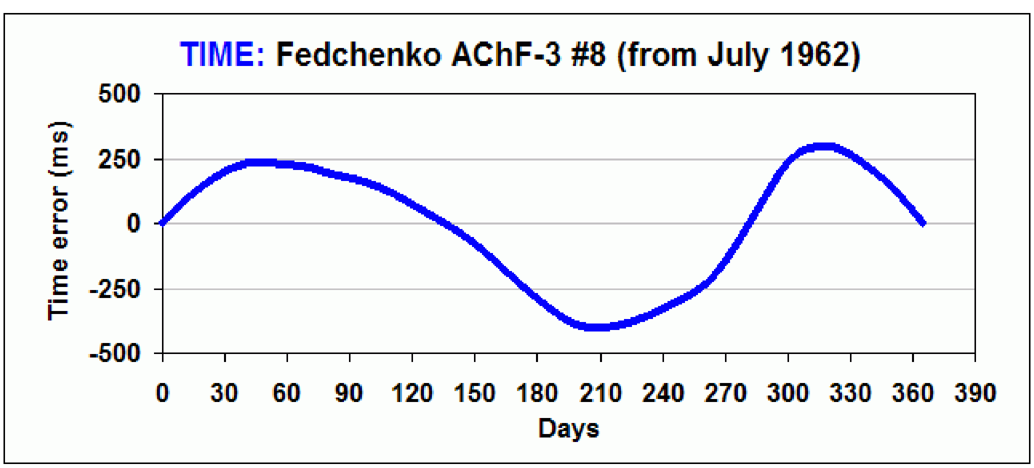
Assuming the original plot was made 50 years ago with real data (and not drawn free-hand) I thought it might be possible to extract raw data *from the plot*. I made a 600 dpi scan of page 261 of Roberts' copy of Feinstein's article, making adjustments with Windows tools (IrfanView and MSpaint). Then I wrote a bitmap processing tool to automatically crawl through the plot, pixel by pixel, paying close attention to exactly where the Fedchenko rate line meandered across the page, logging the exact x and mean y locations of the line. The line was on average 13 pixels high. The following images give a view of the pixel decoding process:





Using the same tools, the x-axis monthly tick marks were found to be about 329 pixels apart (12 months is 3947 pixels). The y-axis tick marks are about 262 pixels apart (each tick represents a 25 millisecond/day rate). With these axis *calibrations*, the measured pixel location of each point in the line was offset and scaled to the original units of days and ms/d rate. This produced two columns of data which were pasted in Excel for plotting or other analysis. The result is a clean digital version of the original Fedchenko rate plot:





The progressive time error plot above is created from the rate data (time error is integrated rate error). It is conventional (but not appropriate in all cases) to normalize the data post-facto by removing the mean rate, which in this case is +47 ms/day. The peak time error values are about -400 ms and +300 ms with a standard deviation of 230 ms; dramatic confirmation that the Fedchenko was able to keep time within 1 second a year. Clocks like this are more stable than the rotation of the Earth itself (ask me about leap seconds sometime).

Allan deviation

Given a rate- or time-series one can also make Allan deviation plots. This was not very successful. The reason, I believe, is that the original plot was a highly filtered version of the raw data. In addition, the process of pixel decoding a scan of a print of a photocopy of a picture of an original document tends to blur points even if they were clear at first. Any artificial smoothing destroys the meaning of an Allan deviation plot: the statistic is intended to show rate **in**stability – and data smoothing, by design, reduces or hides instability in raw data.

This is not the first time I have extracted data from plots in vintage books or articles. Regardless of how well one extracts data, a danger of an old plot is that you don't know how the data was collected or how the data was manipulated prior to plotting. Some old plots are handmade and this adds distortion. In addition, an author may perform averaging to smooth the data and enhance clarity, yet this destroys subtle variations that were in the original raw data.

So I am going to call this attempt at extracting raw data from a plot only partial success. My Excel plot looks identical to the original plot, I was able to create the corresponding time error plot, but the raw data did not lend itself to useful Fourier or Allan deviation analysis.

Decoding a rate plot (short-term stability)

The other plot from the Fedchenko article that really got my attention is shown here:

One square in the vertical direction:
Curve No. 1 (solid)- 100 μsec. in the hour rate of AChF-3.
Curve No. 2 (dashed)- 0.027 milligal

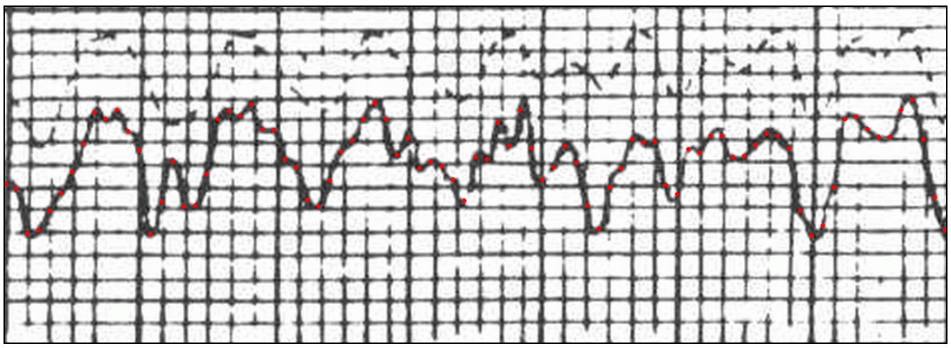
Figure 26. Lunisolar variation in the force of gravity and its effect on the AChF-3 clock.

The photo quality is poor and the plot appears to be hand-made (remember, no personal computers in 1969) but it beautifully shows the effect of tides on the rate of the Fedchenko. The plot is from September, October and

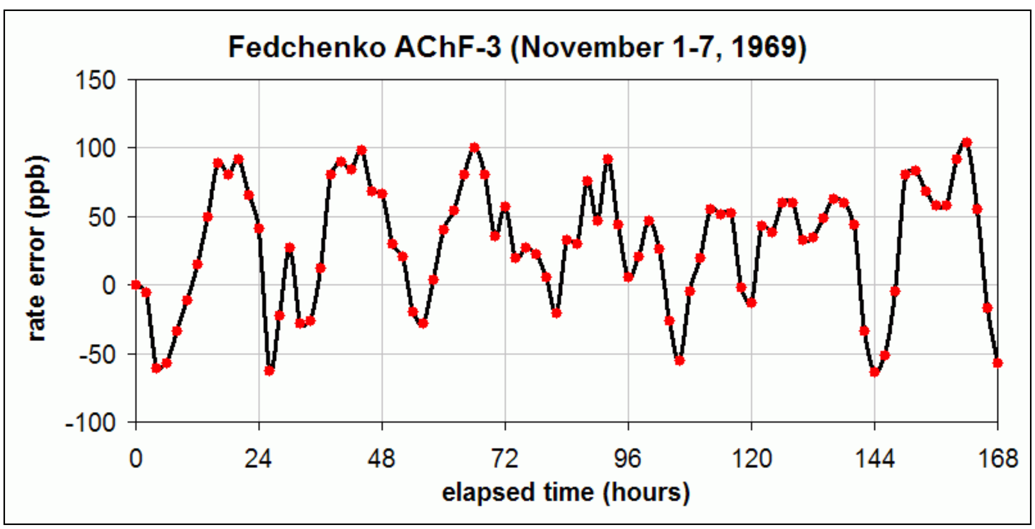
November, for the years 1968 and 1969. Points are plotted every 4 or maybe every 2 hours. Of course it would be nice to have the raw data for this plot too.

My automatic pixel decoding tools did not work on this low-contrast, cluttered plot. But I thought it would be possible to manually recreate the raw data from a representative portion of the plot. The plot was clipped and zoomed so that the squares were 20x20 pixels each (that's 840x300 pixels for 7 days). Note the x-scale is 4 hours per grid and the y-scale is 100 µs/hour (which is 2.78e-8 or 28 ppb) per grid.

I manually followed the trace and placed a red dot every 2 hours in MSpaint. The x,y location of these dots were recorded into Excel, offset and scaled. This gave me an accurate raw data set that seems to match the original plot within the accuracy of the plot itself:



Having extracted the data, here is a clean digital version of the same plot:



With significantly greater effort one could decode all three months of late 1969, but even one week of clean data like this is enough to make a rough Allan deviation plot. Then again, while we are resigned to use Fourier methods or Allan deviation statistics to "see tides" in Shortt or other clocks, the effect of tides in Fedchenko data is so obvious in even a simple rate plot that no further processing is needed.

This 7-day Fedchenko rate plot illustrates another lesson for those building their own pendulum clocks with the goal of detecting tides. Once set up and running, and if the clock is good enough, the characteristic effect of tides will be visible within a few days – just from looking at an hourly rate chart. One does not need to collect massive amounts of data and perform fancy spectral analysis or even make Allan deviation plots.

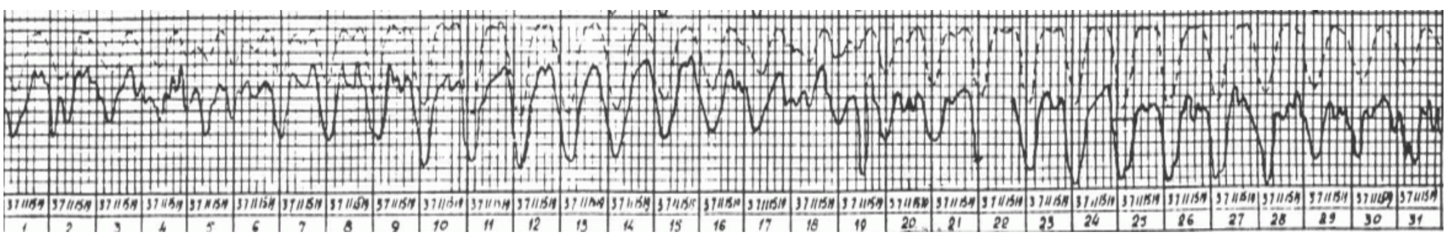
Just as one would suspect from the simple equation $T \approx 2\pi\sqrt{(L/g)}$, when g changes a little, T also changes a little. So if rate measurements are stable down at the tens of ppb level, then the effect of tides on rate should appear. If rate measurements are not stable below the 100 ppb level, then one should address the inherent stability issue first. Waiting to collect more data won't fix that problem. One can determine the hourly rate stability of a clock within minutes to hours at most; there's no need to wait days or weeks or months.

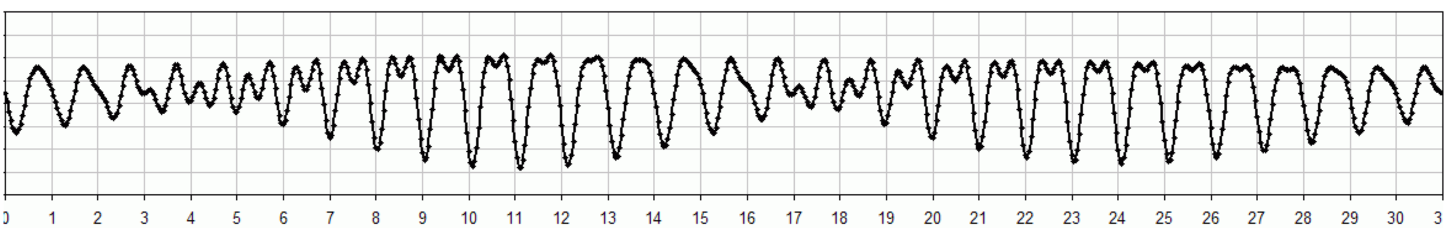
Fedchenko, the gravimeter

With such sensitivity to gravity one can ask if AChF-3 is really a clock, or just a gravimeter. The answer is that all the best clocks are essentially gravimeters, and Fedchenko is the Holy Grail of pendulum clocks.

Unlike climate and weather, the wonderful thing about tides is that the position and motion of the earth-sun-moon system is knowable with high accuracy for the future, present or past. For this series of articles on tides I wrote software tools that create earth tide tables for any given date, latitude and longitude. Setting these parameters to Kharkov, USSR on November 1st, 1969 allows us to know the predicted gravity at that distant place and time.

The first plot below, extracted from the bottom row of figure 26, shows the measured hourly rate of the Fedchenko clock for all days in November, 1969. Try to ignore all the grid lines and dotted lines. The dark trace is the ***measured*** pendulum rate:





The second plot above shows changes in gravity as ***predicted*** by my earth tide prediction program. The agreement between the two plots is near perfect, and they were produced 50 years apart.

Fedchenko, the seismometer

With such sensitivity to (the acceleration of) gravity it should not be surprising to learn that the Fedchenko clock also makes a good seismometer. A few years ago I ran across a wonderful paper by three scientists from Nikolaev, Ukraine describing this in detail. The title is "The Anomalies of Fedchenko Astronomic Clocks Readings before Some Large Earthquakes". I have a copy if you are interested.

Conclusion

Fedchenko is a stunning example of a pendulum clock, often credited as the best in the world. It proves that an extremely well-built pendulum clock can be so stable that the only disturbance to its timekeeping is tidal changes in gravity. AChF-3 is so stable that one doesn't need to resort to statistical processing to uncover the effect of tides.

Superb short-term stability does not necessarily translate to superb long-term stability. Long-term mechanical or operational drift or slowly changing environmental effects will impact timekeeping over years. However the clock appears capable of long-term performance on the order of a second per year.

One can ask why the AChF-3 is such a good clock. Credit is usually given to the unique isochronous suspension or the analog E/M impulse method. My answer is that unless I see actual measurements, I don't know what percent each element in the design is responsible for its high stability. This would be a great research topic.

A copy of my pendulum papers is at www.LeapSecond.com/hsn2006/ and raw data for some pendulum clocks is at www.LeapSecond.com/pend/ as well as scans of some plots and documents.