Extreme Amateur Timekeeping: from Harrison to Einstein

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NAWCC Ward Francillon Time Symposium
TIME for Everyone
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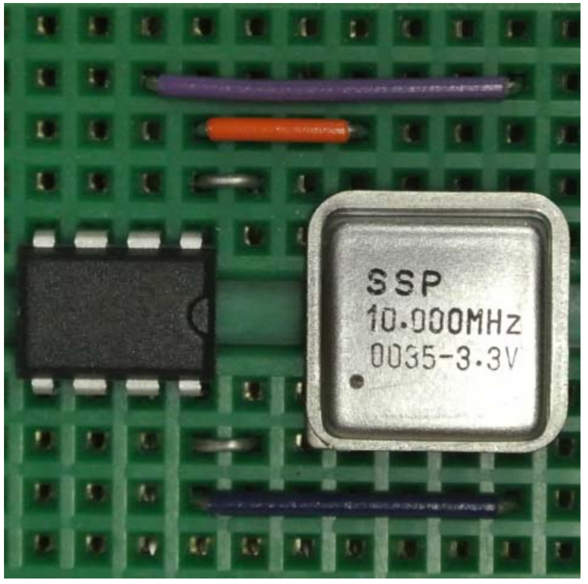
Outline

- Part 1 – amateur timekeeping
- Part 2 – precision pendulum clocks
- Part 3 – powers of ten
- Part 4 – kids, clocks, and relativity

1. amateur timekeeping

- An innocent beginning, 20 years ago
- LED clock project, quartz timebase
  - how accurate is it?
  - how to measure it?
- Use frequency counter
  - how accurate is it?
  - how to measure it?



Accuracy

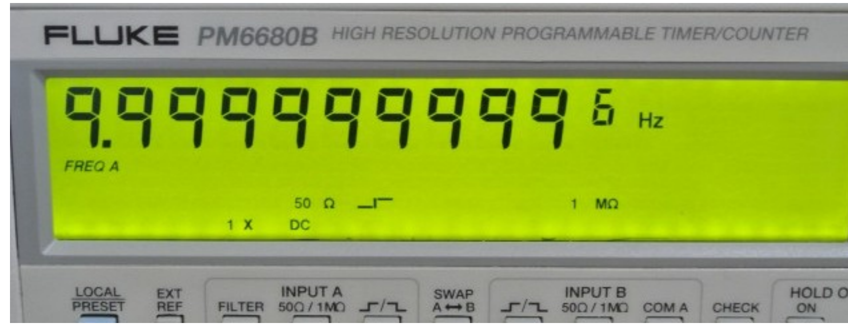
- 0.01/10.00 MHz = 0.1% (86 sec/day)
- 0.0001/10 = 10 ppm (0.8 sec/day)

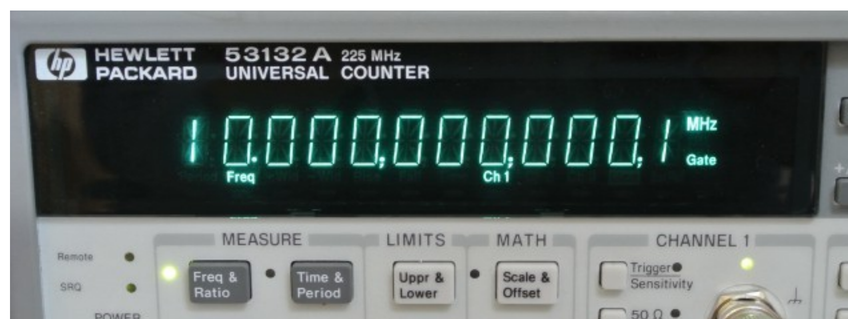
More accuracy

- Better timekeeping needs better timebase
- Better measurement requires better counter and/or better reference
- What does it mean to “keep” time?
  - who’s time are we actually keeping?
  - what is WWVB, GOES, Loran-C, GPS time?
  - what is UTC; how good are atomic clocks?
- This time stuff is all so interesting

The quest for better oscillators

The quest for more digits





Slippery slope

- More oscillators, more test equipment
- Oscillator measurement and comparison
  - quartz, rubidium, cesium standards
- Improve counter speed and resolution
  - microseconds, nanoseconds, picoseconds
- Books, articles, op/svc manuals, HPJ
  - bad case of precise time & frequency curiosity
- Help! I’ve got the *“time bug”*

Home time & frequency lab

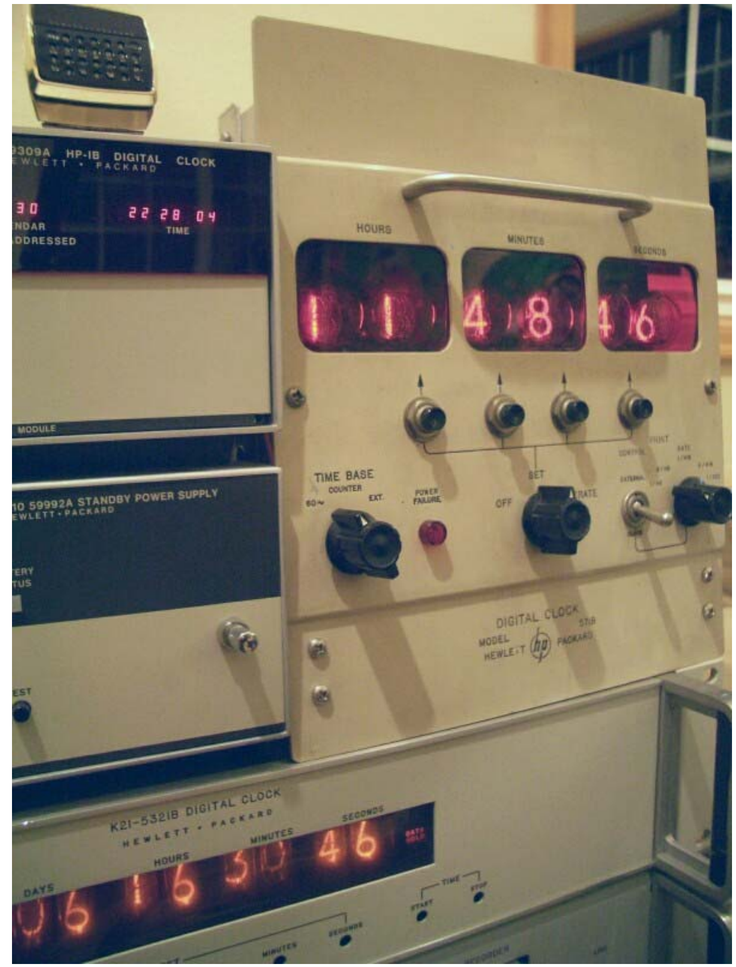
Museum of *hp* clocks

HP quartz

- 105B
- 107BR
- 106B
- 104AR
- 103AR
- 101A
- 100ER

HP clocks

- HP01
- 571B
- 5321
- 117A
- 114BR
- 115BR
- 113AR



HP cesium & rubidium

- 5071A
- 5065A
- 5062c
- 5061B
- 5061A
- 5060A

Vintage *hp* 5061A (eBay)

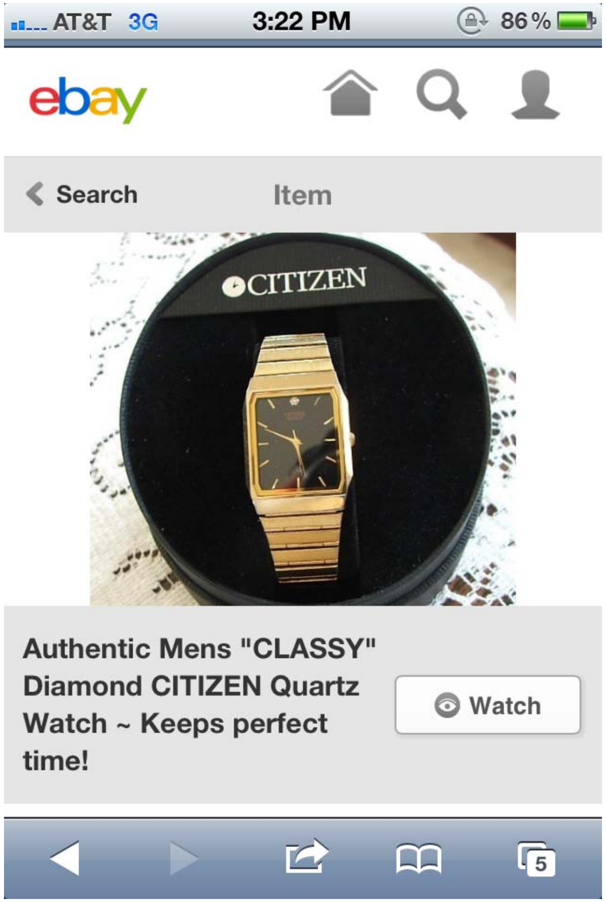
FYI: cesium (caesium)

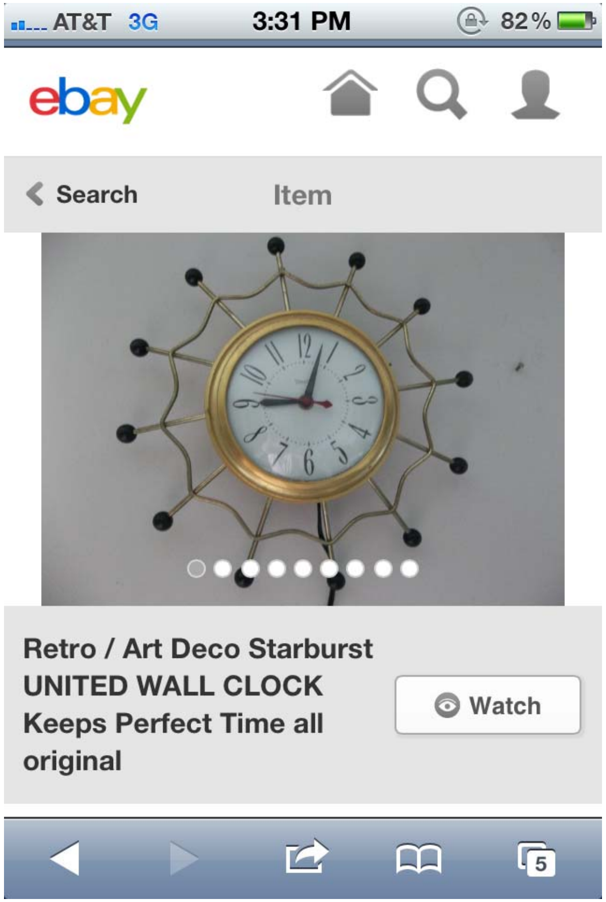
- Cesium atomic clocks are ***not*** radioactive
- They use a natural, stable Cs^{133} atom, not the scary man-made *radioisotope* Cs^{137}
- Analogy: C^{12} vs. C^{14}
- K^{39} vs. K^{40} (banana)
- "hyperfine transition" 9,192,631,770 Hz
- Solid / liquid metal

What is the *best* clock?

- Quartz: inaccurate and drifts
- Rubidium vapor: more stable but still drifts
- Cesium beam: better still and no drift
- Hydrogen maser: most stable, small drift
- UTC itself is “average” of 345 clocks
- Exotic fountain, ion, optical clocks
- No one best clock, no *perfect time*

“Keeps perfect time”





Which watch is best?

- You go shopping for watches at lunch…

Which clock do you want?

- Checking each day, at precisely noon:
- (a) (b) (c) (d)
- 12:00:00 12:01:30 12:03:30 12:06:11
- 12:00:00 12:01:40 12:03:25 12:07:22
- 12:00:00 12:01:20 12:03:30 12:08:33
- 12:00:00 12:01:10 12:03:35 12:09:44
- 12:00:00 12:01:40 12:03:30 12:10:55
- Which one do you want to buy?

Which clock do you want?

- Answer:
  - (a) is probably a stopped watch
  - (b) is most accurate, but more variable
  - (c) is less accurate, but less variable
  - (d) is least accurate, but very stable
- Watch (d) is exactly 1:11 fast per 24h
  - regulate (or simply apply a math correction) and then you have the best watch

Best wristwatch

2. precision pendulum clocks

- My timekeeping world expanded in 1995
  - Bill Scolnik (pendulum and atomic clocks)
  - Dava Sobel (*Longitude*)
- New appreciation of historical timekeeping
  - NAWCC, HSN(161), books, articles, *people*
- Amazing world of horology, and again:
  - how accurate is it?
  - how to measure it?

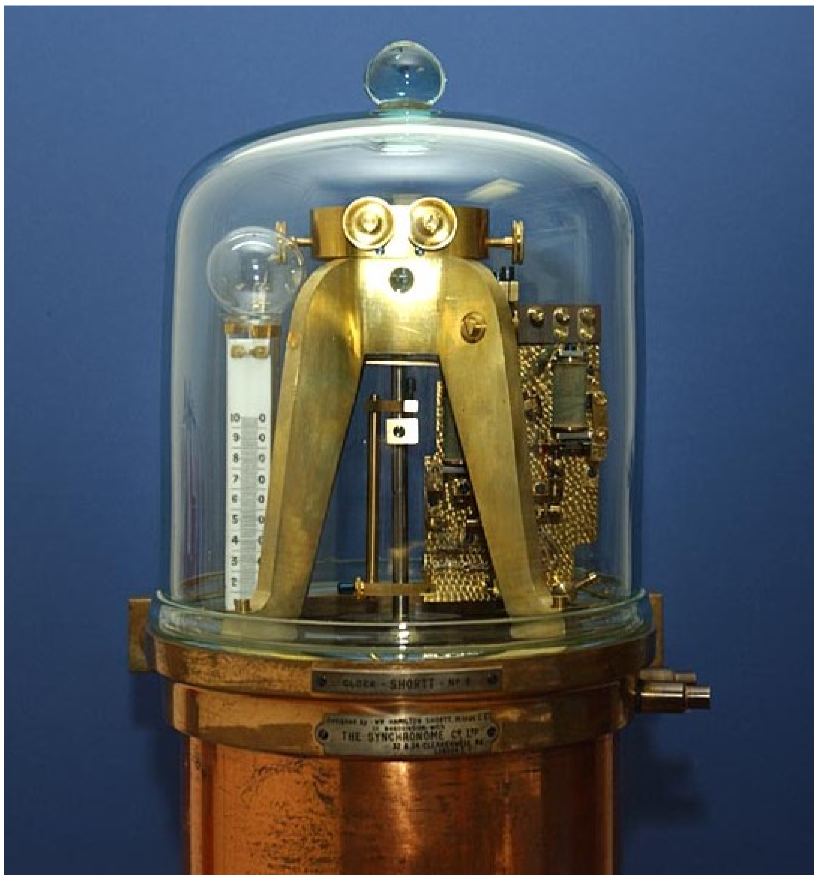
Precise pendulum clocks

- Classic examples:
  - Riefler, Shortt, Fedchenko, and more
- Modern amateur examples:
  - Philip Woodward (W5)
  - Douglas Bateman
  - Bill Scolnik (Q1, Q2, Q3)
  - Teddy Hall (Littlemore)
  - Bryan Mumford, and more
- No amateur has out-performed a Shortt

Pendulum clock, tides

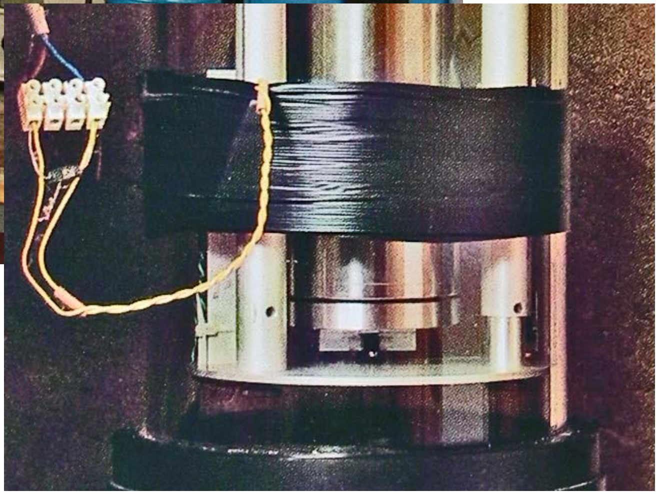
- The issue with lunar-solar "earth" tides:
  - period $T \approx 2\pi\sqrt{(L/g)}$
  - g (980 gal) varies by about ±100 µgal
  - in theory, this affects rate and timekeeping
- Earth-moon-sun system is complex
  - timekeeping error does not average to zero
  - this limits [best] pendulum performance
- Let's study 4 examples

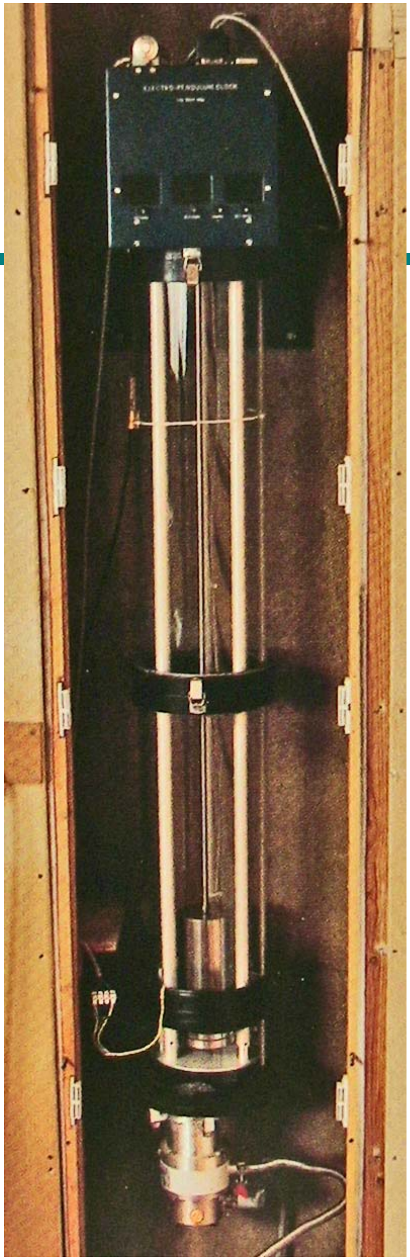
Shortt-Synchronome



Fedchenko AChF-3

Littlemore clock





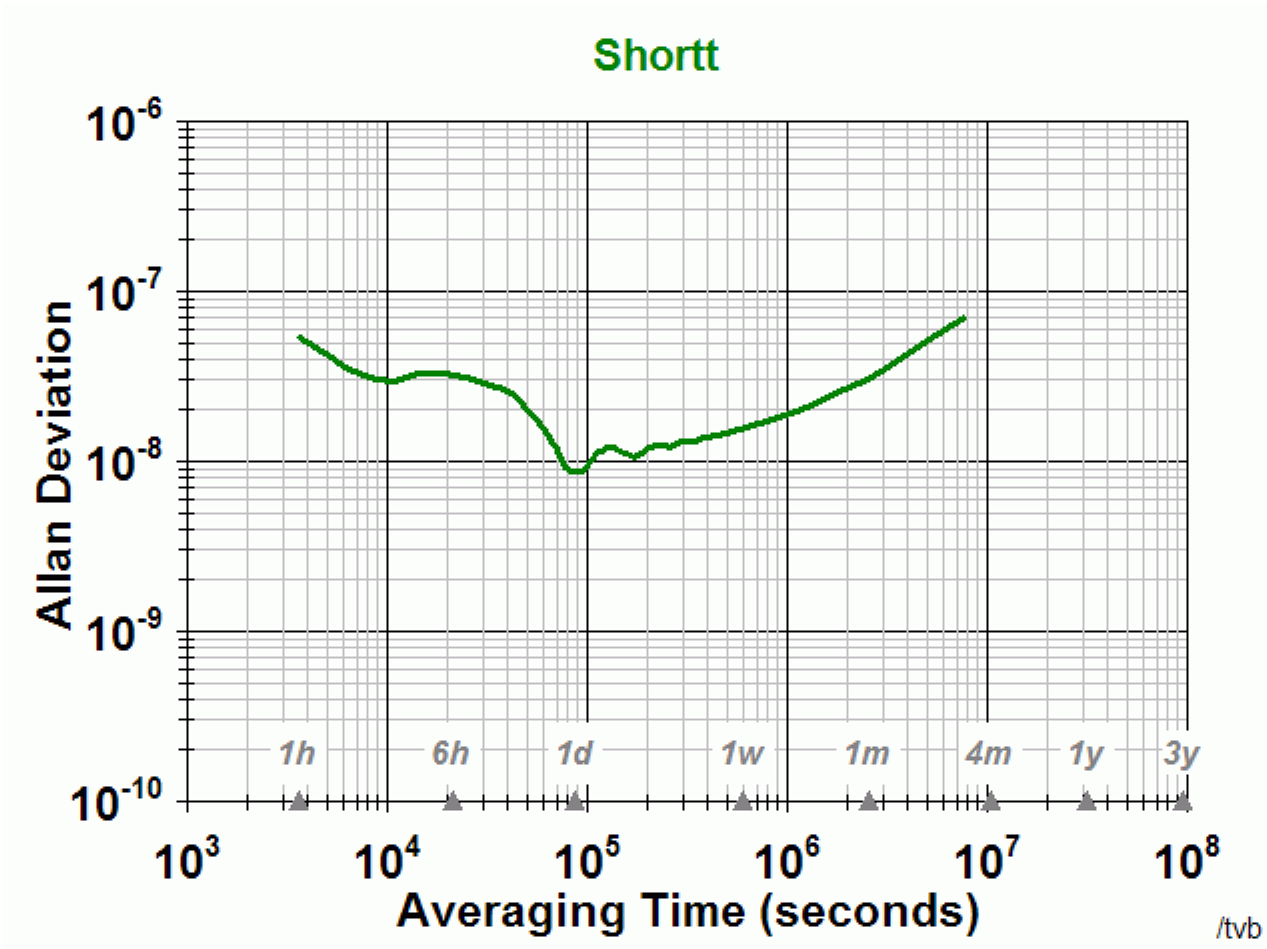
Pendulum [in]stability

- Performance comparison:
  - 1. Shortt #41 (data from Pierre Boucheron)
  - 2. Fedchenko #8 (partial data)
  - 3. Littlemore (data from Teddy Hall)
  - 4. “Perfect” (computer *model* of gravity)
- Allan deviation statistics
  - short-term perturbations
  - long-term drift (environment, amplitude)

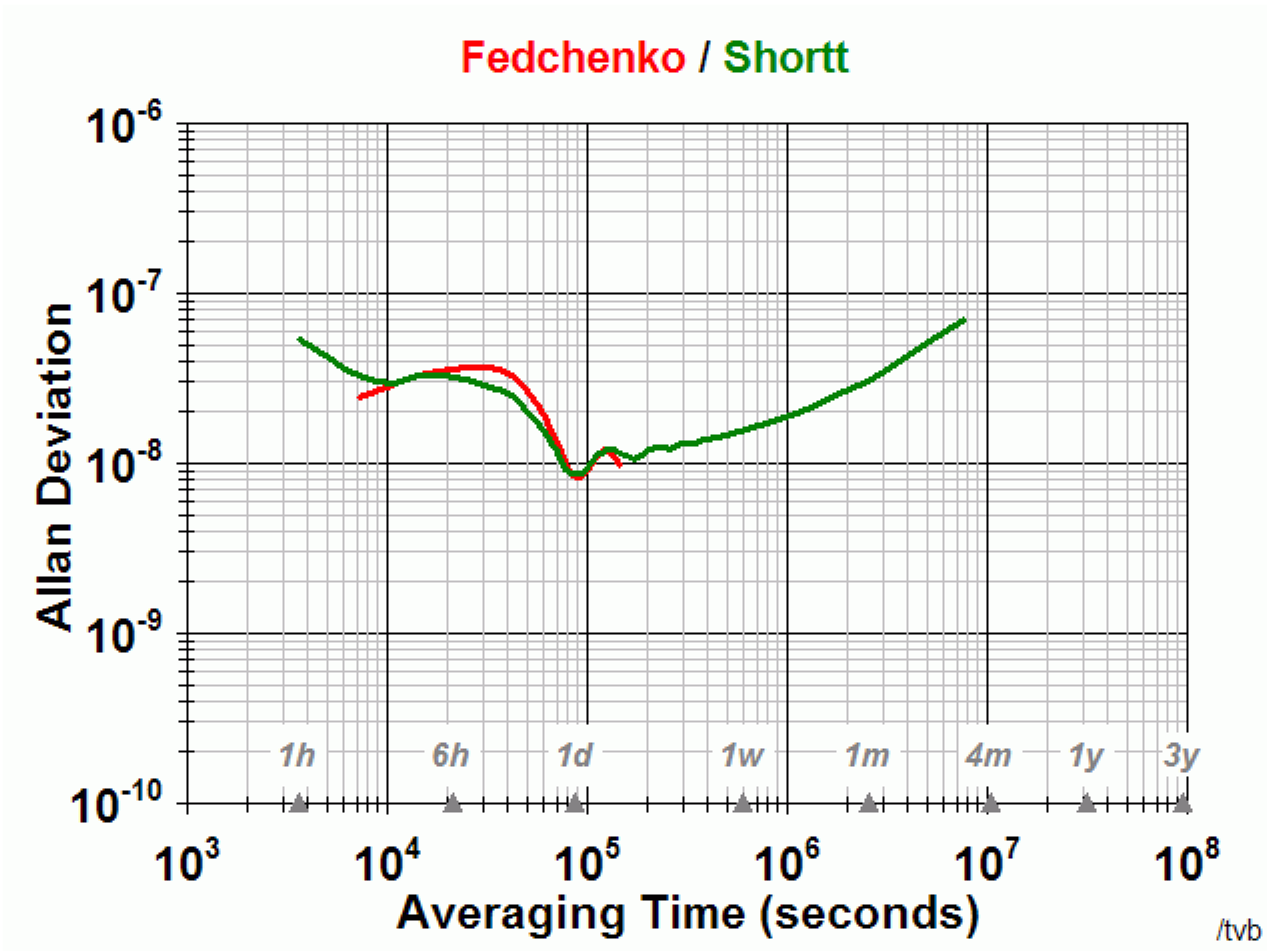
Allan deviation

- Mean, *standard deviation*, regression, …
- Clock performance can be more complex:
  - 2nd difference method is useful
  - notion of sampling interval is useful
- Allan deviation incorporates both
  - a measure of frequency instability (*sigma*)
  - as a function of sampling times (*tau*)
- Comparison of similar and different clocks

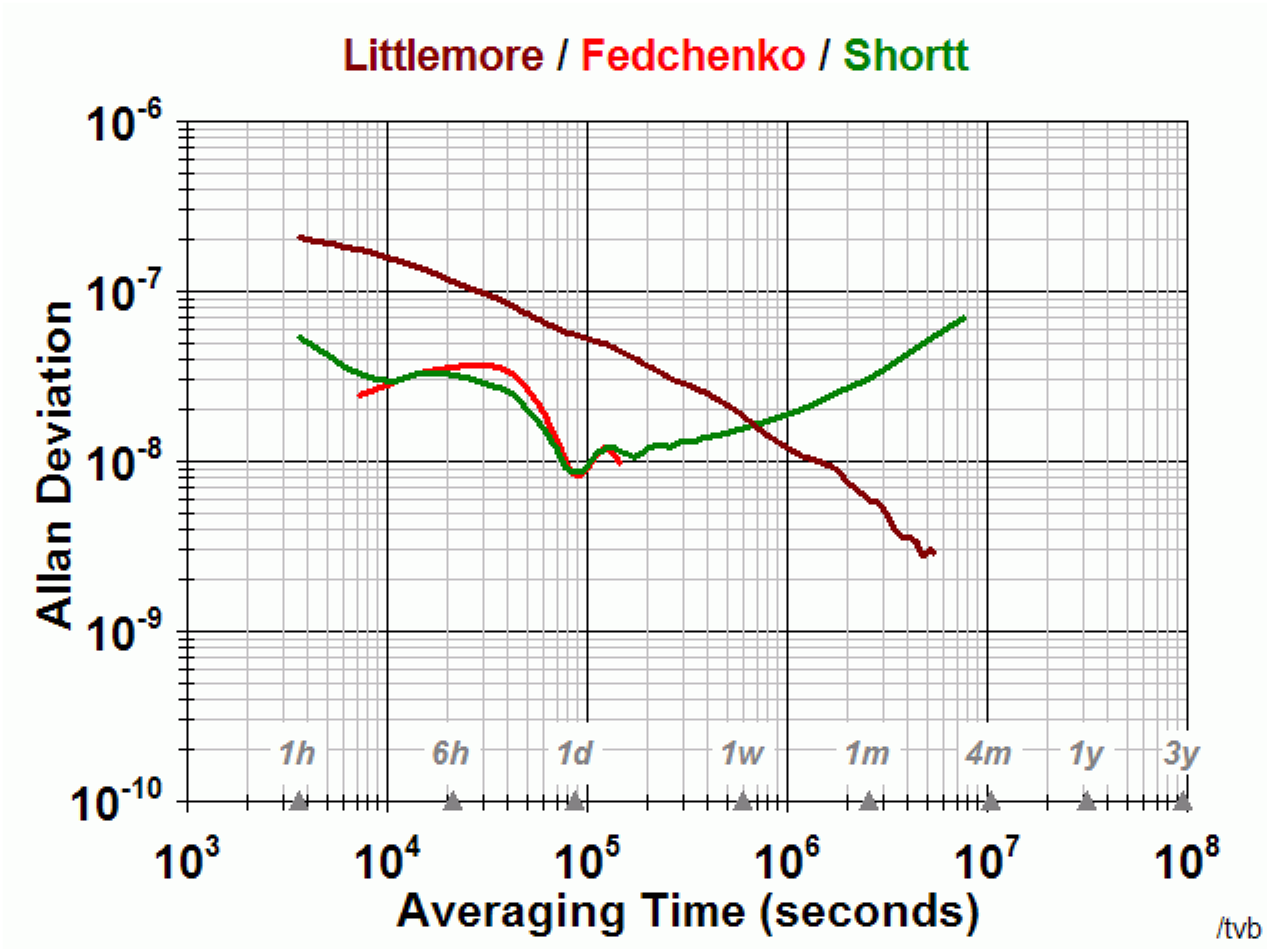
Pendulum instability(1)



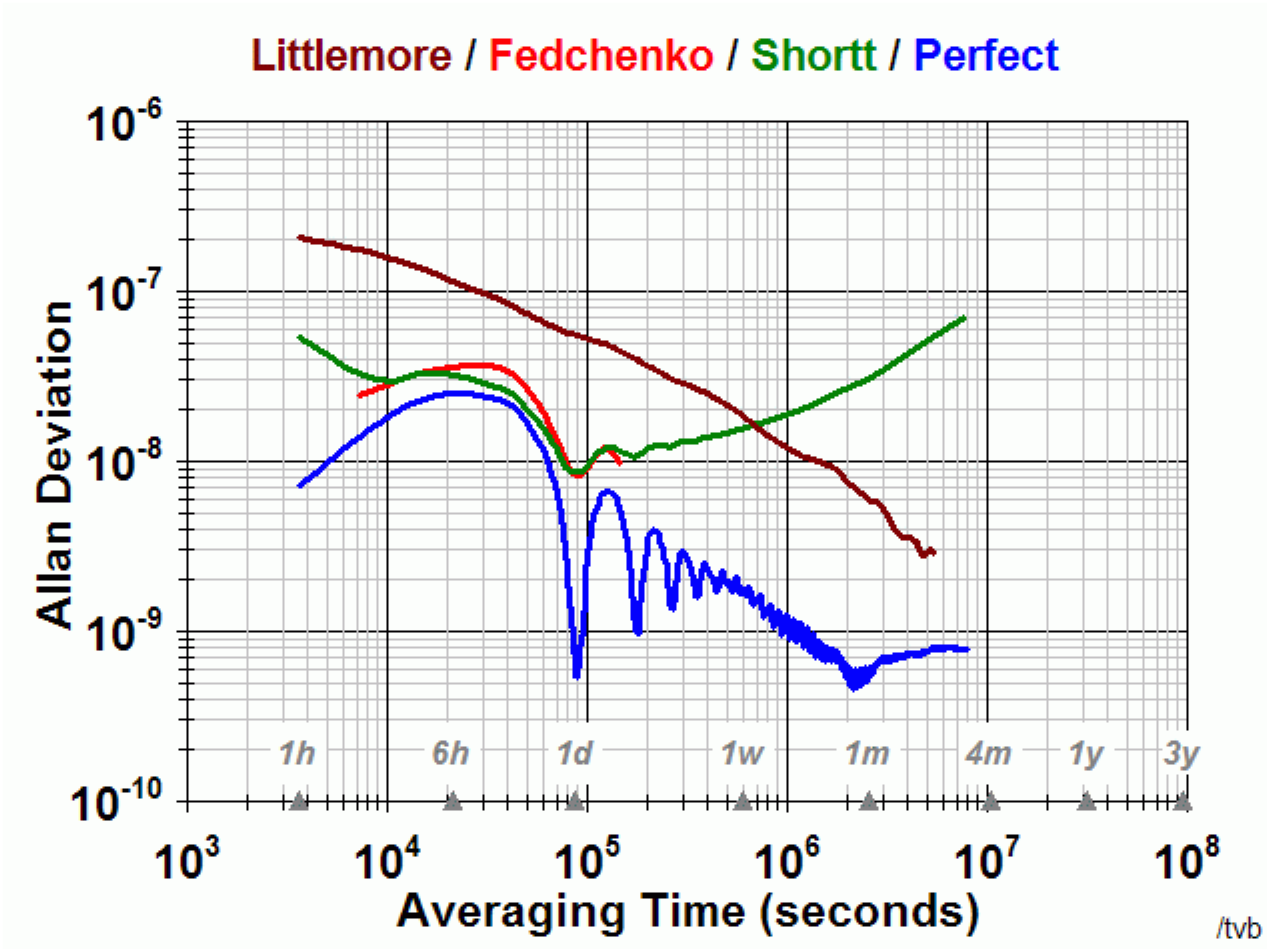
Pendulum instability(2)



Pendulum instability(3)



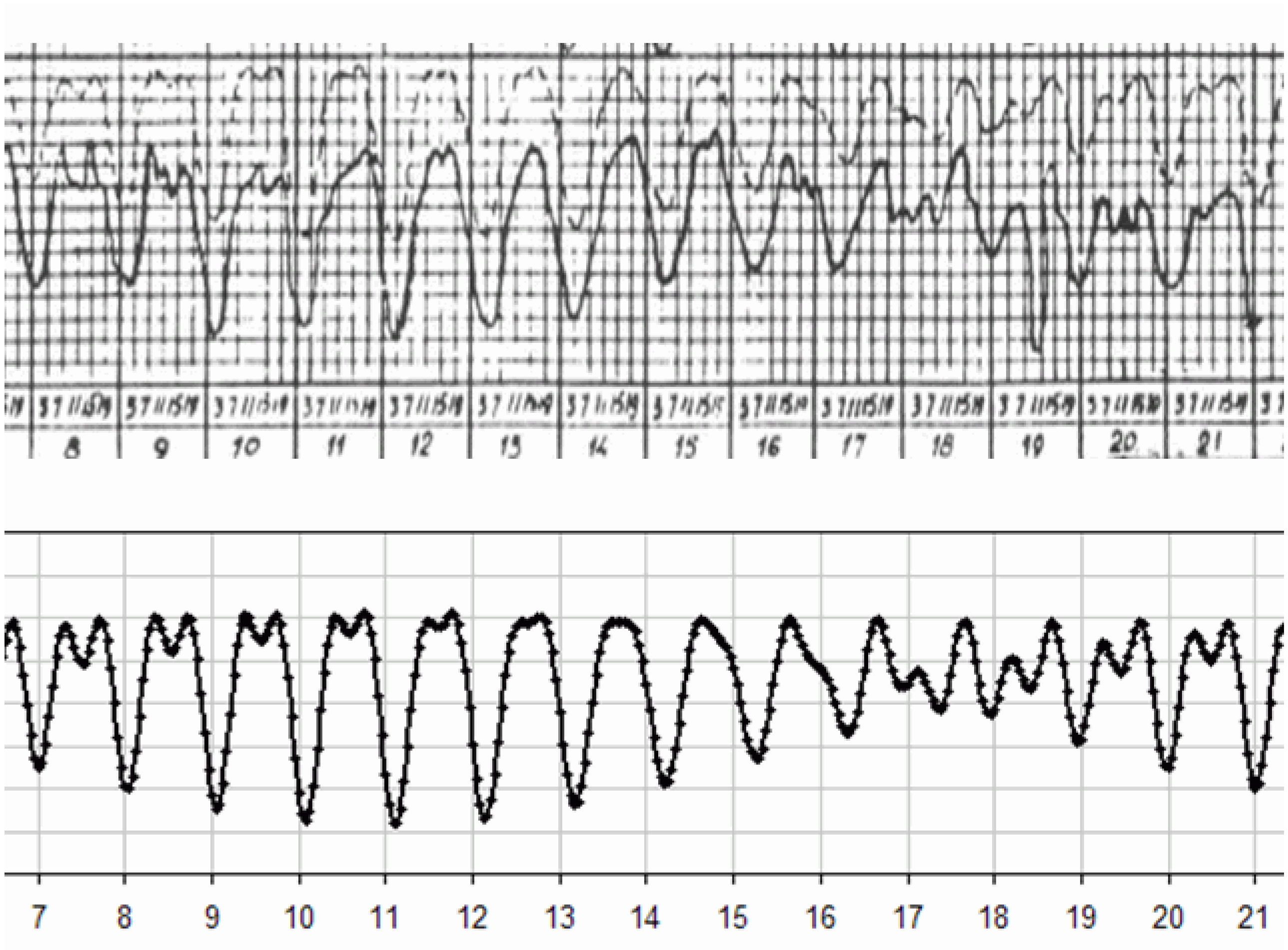
Pendulum instability(4)



Pendulum insights

- There is still room for improvement!
  - Shortt, Fedchenko hit short-term limit
  - Shortt is 100x from perfect, long-term
  - Littlemore, even using quartz, is still 10x
- Someday, someone will better this
  - will it be you?
  - with free pendulum or hybrid quartz?
- Best pendulum clock is a good gravimeter

Fedchenko (gravimeter) 11/69



3. powers of ten

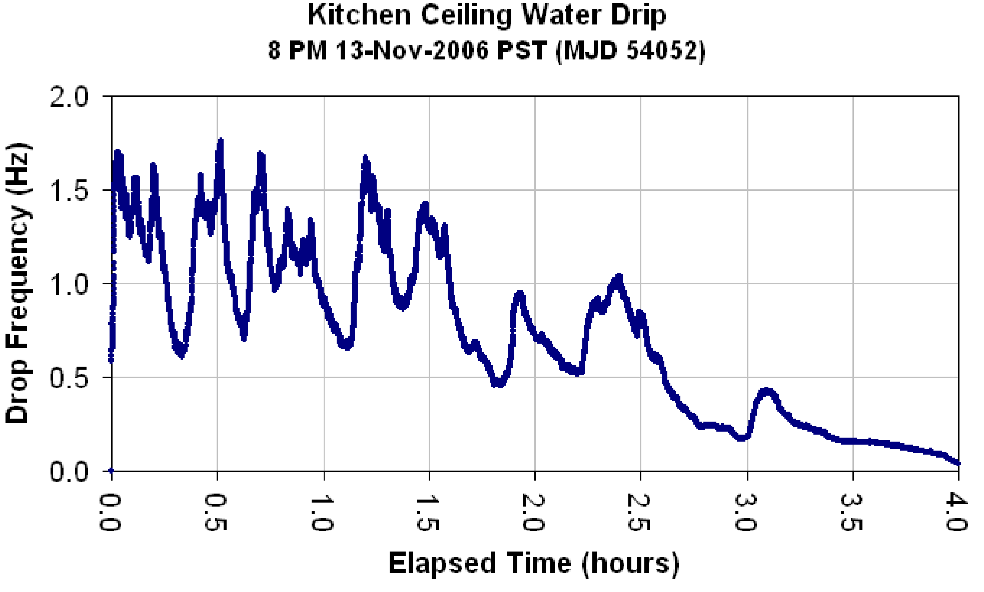
- Not all clocks are super accurate
- <u>Any</u> periodic event is can be a clock
- How *regular* the occurrence determines:
  - how *good* or *bad* the clock is
- How *continuous* the events determines:
  - how *reliable* the clock is
- The range of accuracy/stability is huge!
  - all you have to do is measure it

“Powers of Ten” – inspiration

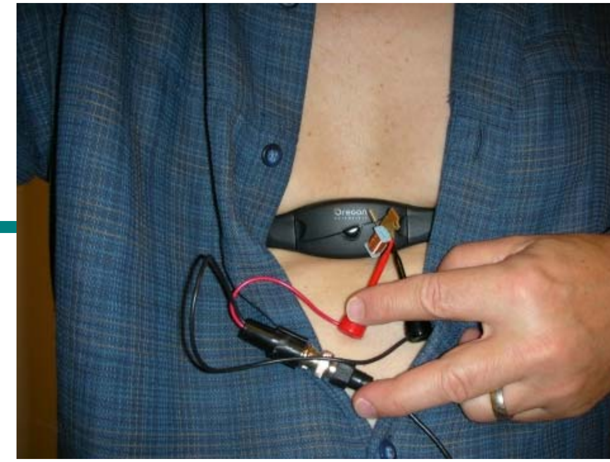
- Mr Charles and Mrs Ray Eames (1977)
  - “the effect of adding another zero”

10^{-0} drip, drip

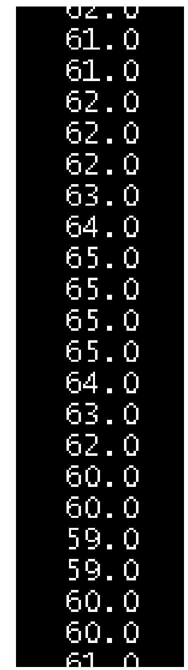
- Leak in ceiling
- 0.57 s … 9.9 s
- 1.7 Hz … 0.1 Hz



10^{-1} heart beat

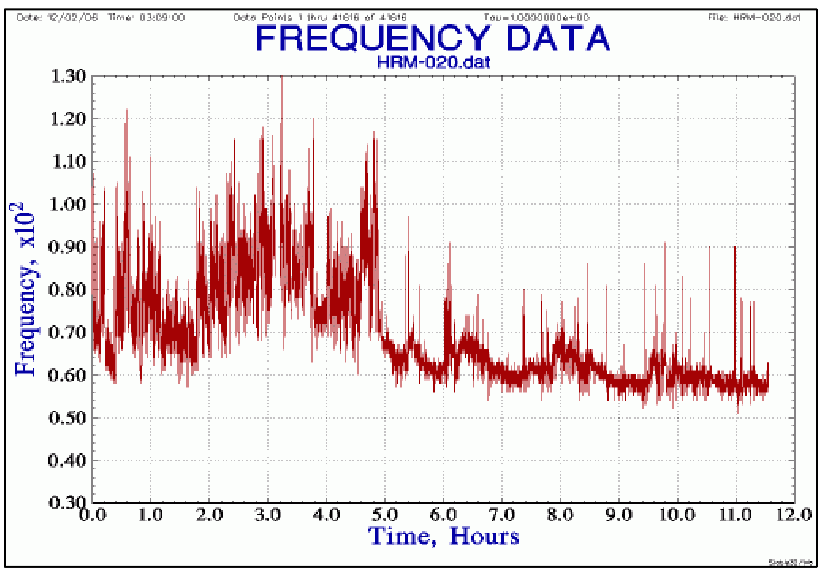


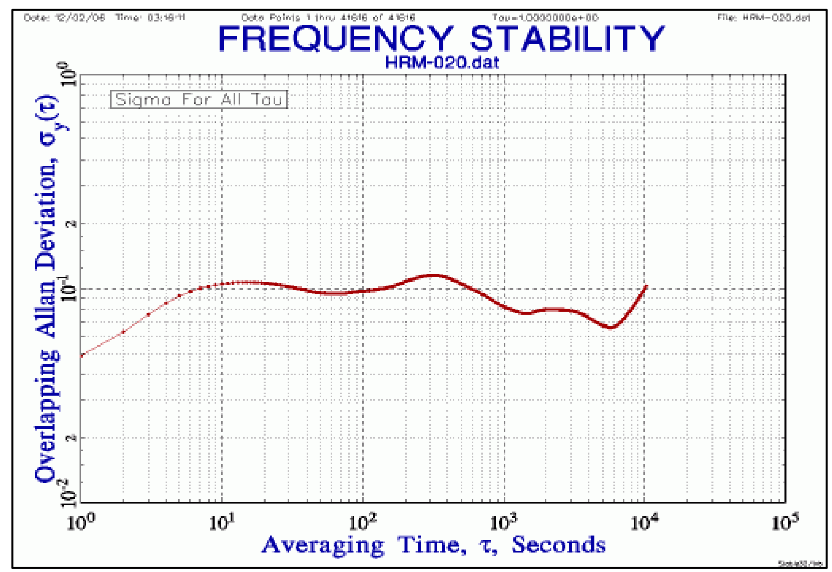
- 10^{-1}, 0.1, 10%
- The original ‘1 PPS’
- Sometimes 2x, even 3x
- Much higher stability at night
- < 10% accuracy possible



10^{-1} heart beat

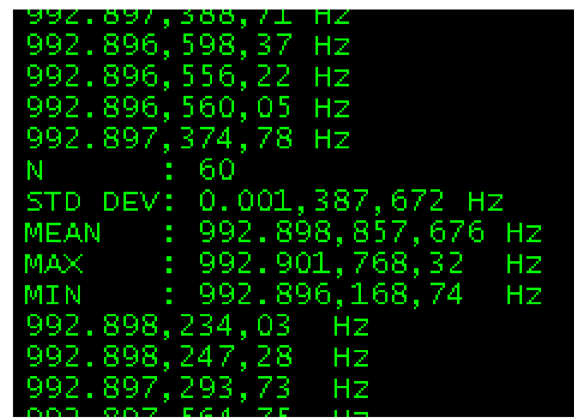
- 12 h frequency plot (evening/night)
- ADEV floor is 10^{-1} from 10^{1} to 10^{4} s!



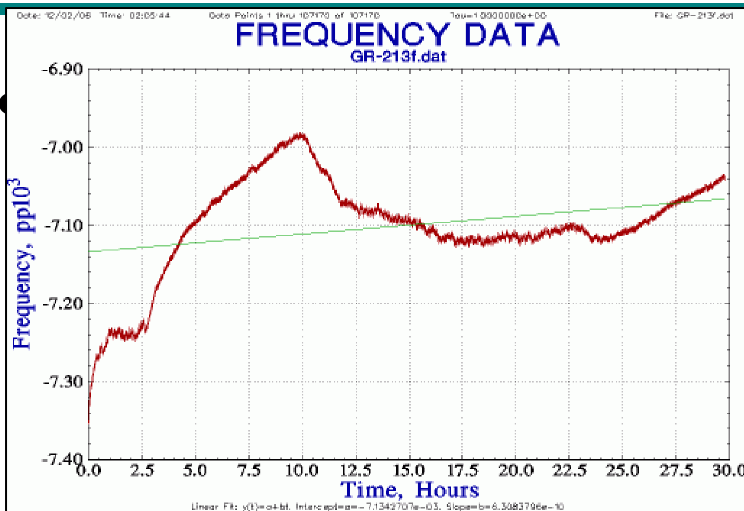


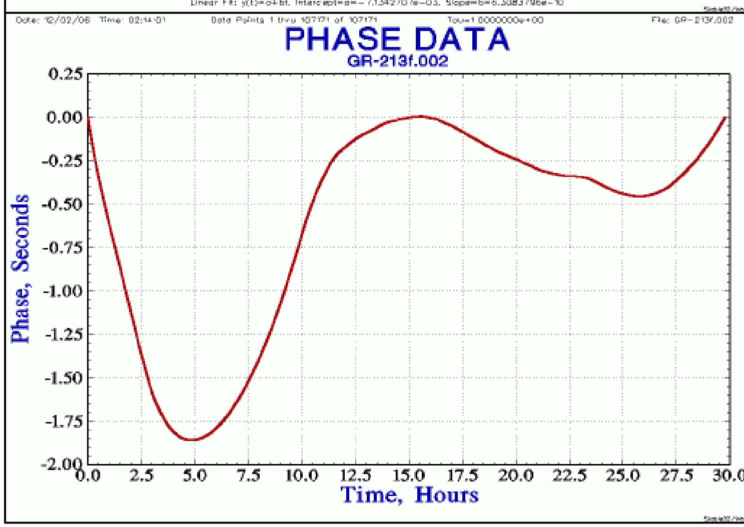
10^{-2} tuning fork oscillator

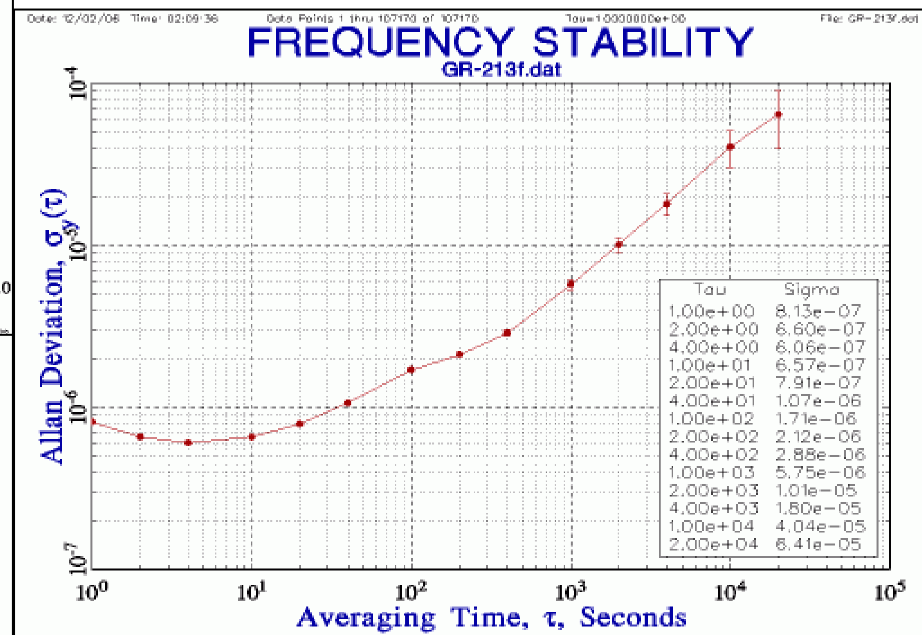
- 0.01, 1%
- General Radio Type 213 Audio Oscillator
- 1 ‘kc’; f = ~**992.8** Hz
- ±1.3 mHz (60 x 1 s)
- Accuracy < 1%
- Count those 9’s
- ADEV is 10^{-6}…10^{-4}


```
992.896,598,37 Hz
992.896,556,22 Hz
992.896,560,05 Hz
992.897,374,78 Hz
N       : 60
STD DEV: 0.001,387,672 Hz
MEAN    : 992.898,857,676 Hz
MAX     : 992.901,768,32  Hz
MIN     : 992.896,168,74  Hz
992.898,234,03  Hz
992.898,247,28  Hz
992.897,293,73  Hz
```

10^{-2} tuning fork oscillator

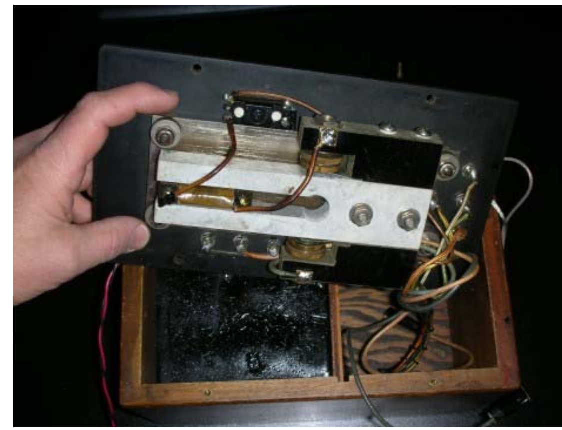


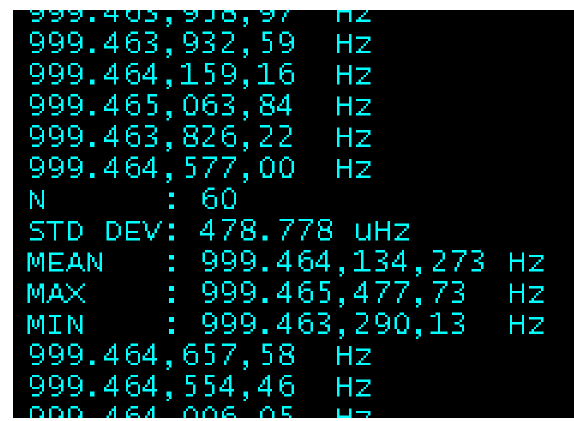




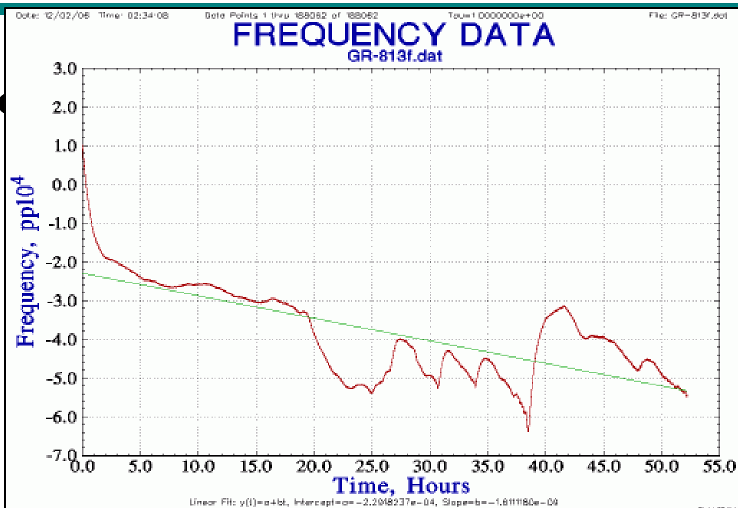
10^{-3} precision tuning fork

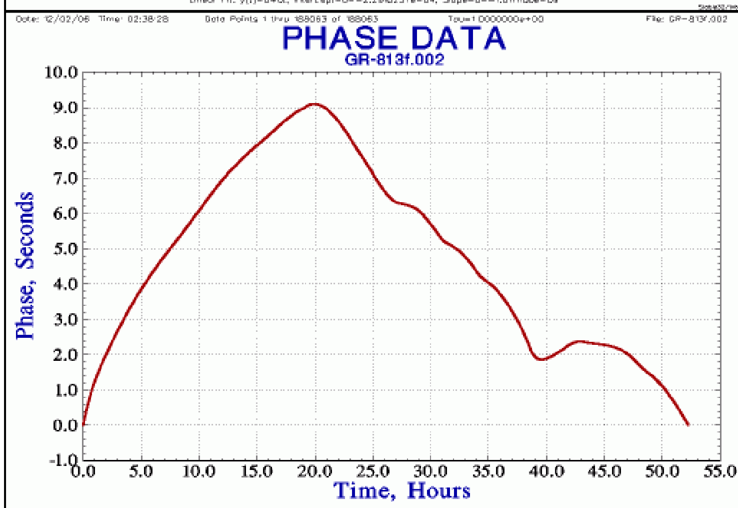
- 0.001, 0.1%, 1 ms/s
- General Radio Type 813 single vacuum tube
- 1 ‘kc’ tuning fork
- f = ~**999.4** Hz
- ±400 μHz (60 x 1 s)
- Accuracy < 0.1%
- ADEV is 10^{-7}…10^{-4}

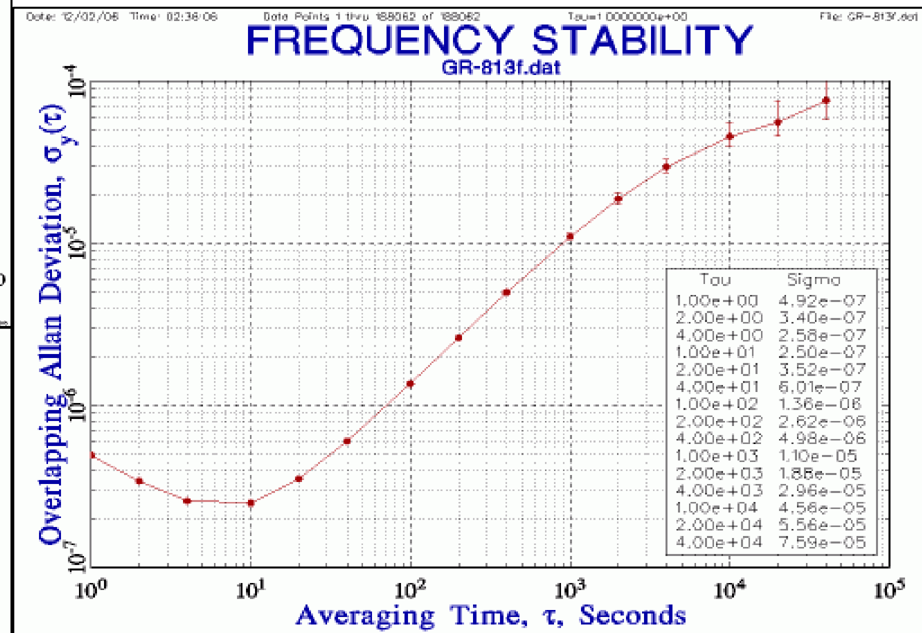




10^{-3} precision tuning fork







10^{-4} mechanical oscillator

- 0.01%, 100 ppm
- Mechanical oscillator transistorized
- “Four 9’s”

```
999.907,211,67  Hz
999.907,250,33  Hz
999.907,273,16  Hz
999.907,311,01  Hz
999.907,250,27  Hz
999.907,345,09  Hz
N       : 60
STD DEV: 151.812 uHz
MEAN    : 999.907,159,334 Hz
MAX     : 999.907,404,05  Hz
MIN     : 999.906,840,54  Hz
999.907,392,20  Hz
999.907,415,25  Hz
999.907,354,85  Hz
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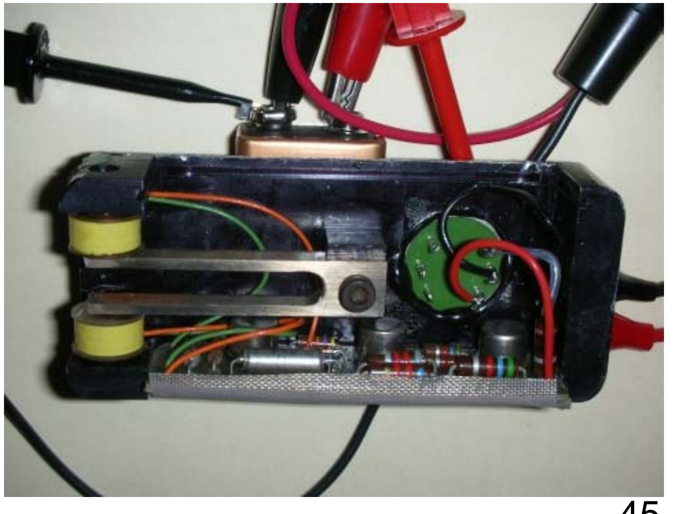
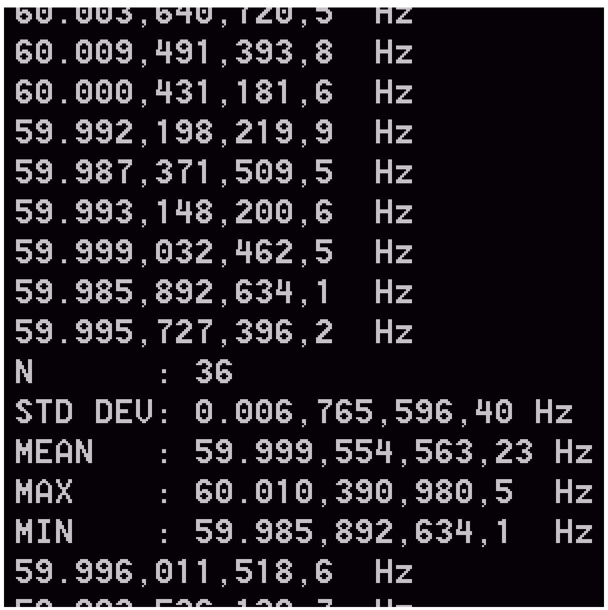
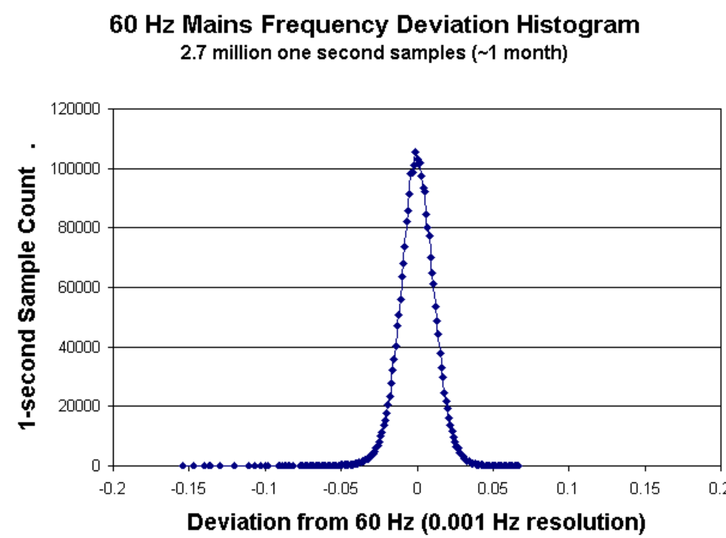


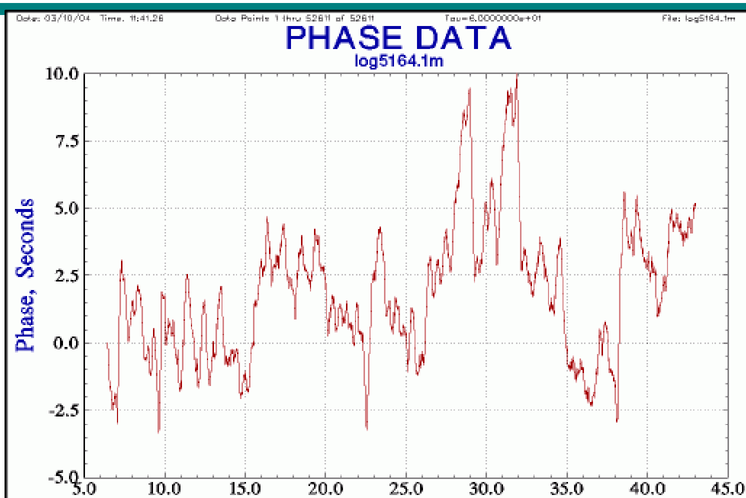
10^{-5} mains (line frequency)

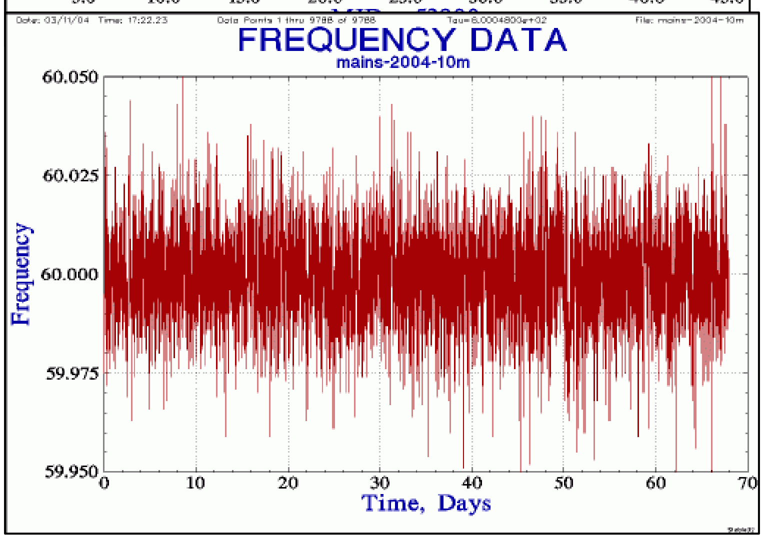
- 0.001%, 10 ppm
- 60± Hz

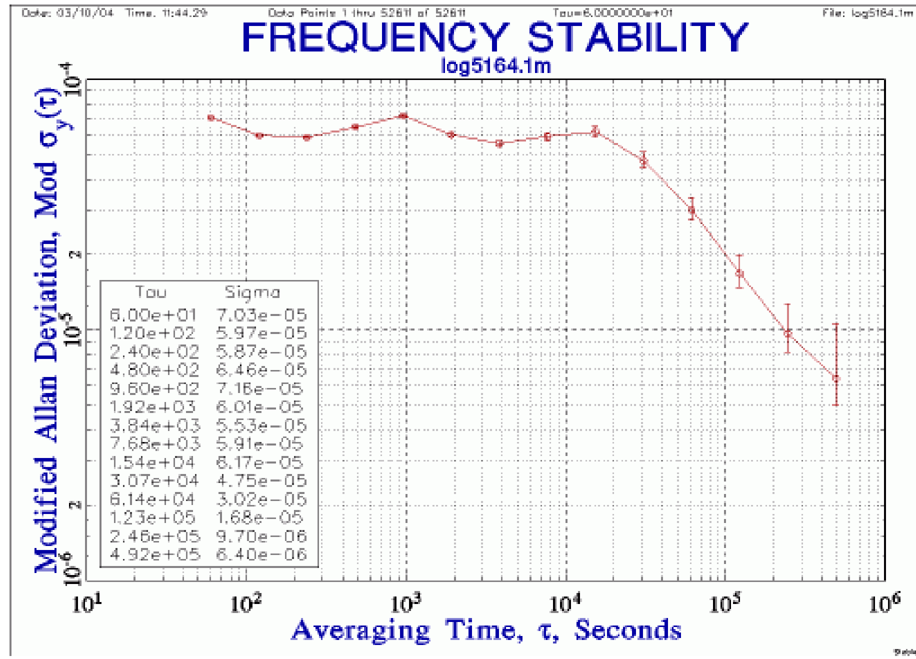




10^{-5} mains (line frequency)

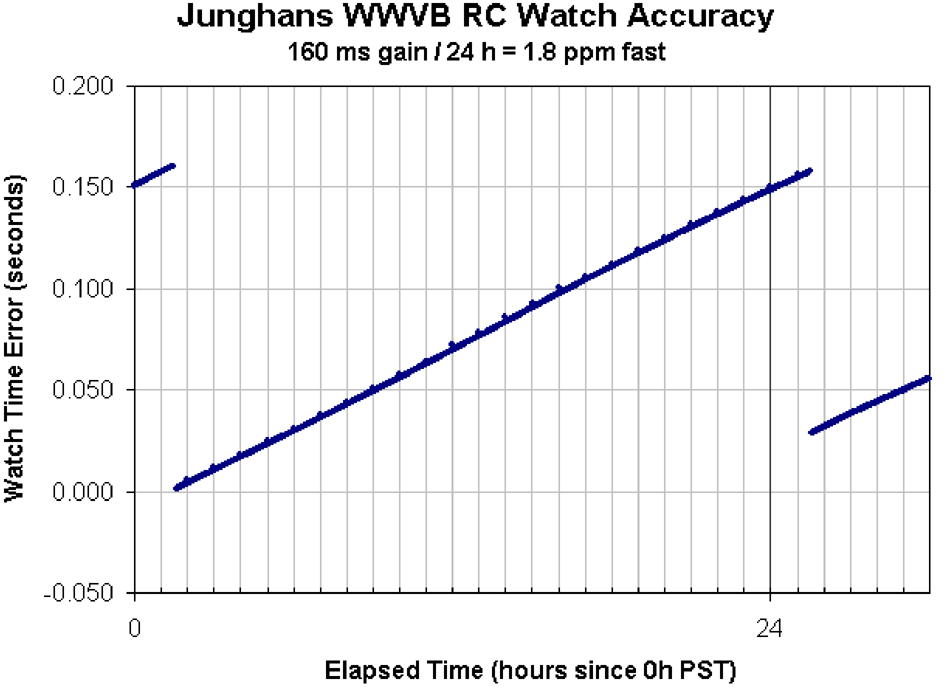






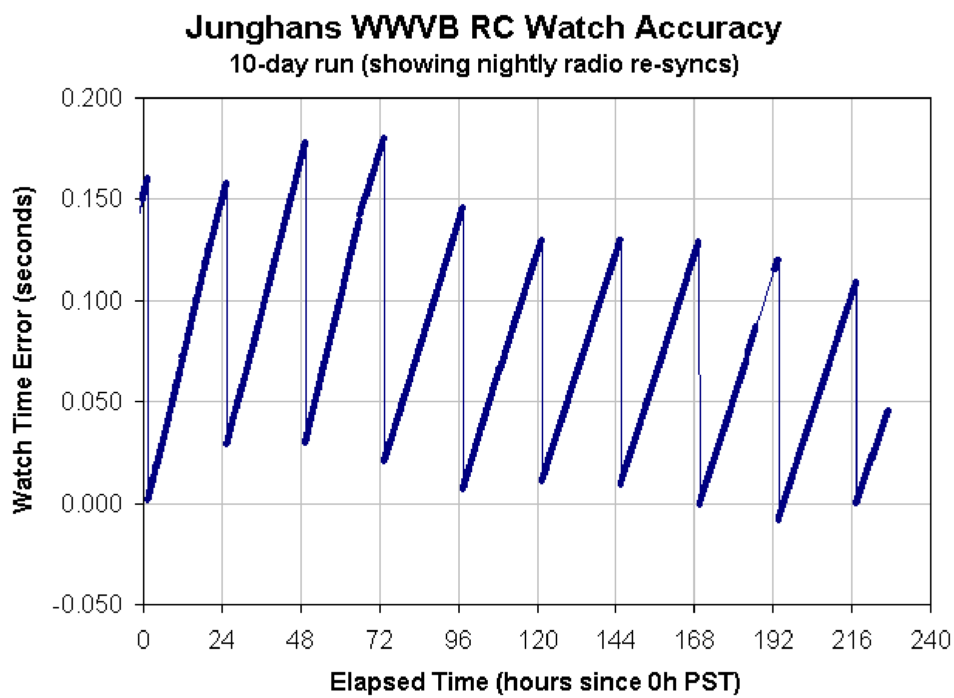
10^{-6} quartz watch (RC)

- 0.0001%, 1 ppm, 1 µs/s
- +160 ms/d = +1.85 ppm



10^{-6} quartz watch (RC)

- Nightly WWVB radio sync (60 kHz)
- Look closely at 01:30 AM PST
- +1h +30m +15s
- Plot of 9 days
- Rate variations
- Sync variations

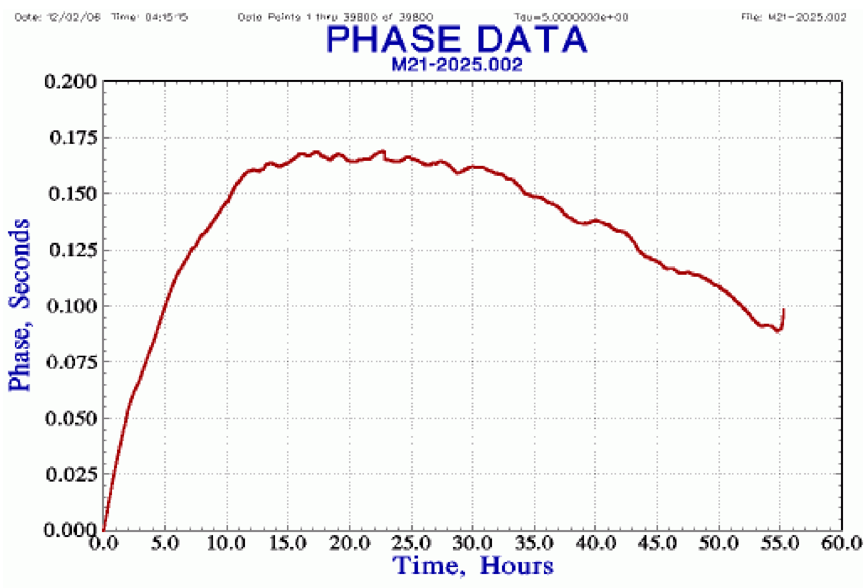


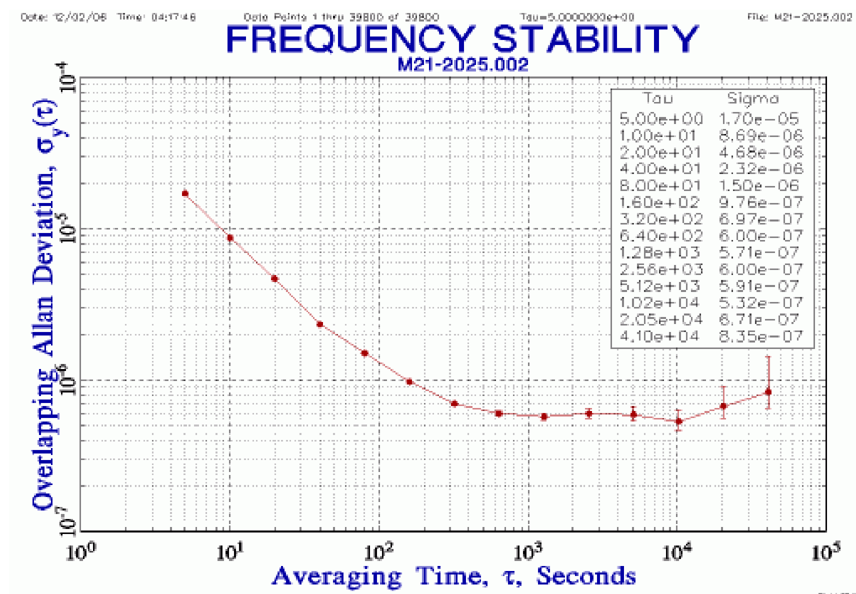
10^{-7} chronometer

- 0.1 ppm
- Rated ¼ sec/day deviation

10^{-7} chronometer

- ~55 hour runtime
- 200 ms phase residuals
- ADEV 6×10^{-7}





10^{-7} chronometer

- From 1940's USN manual…
- Phase
  - Dial error
- Frequency
  - Daily rate
- Drift
  - Deviation in rate

COMPUTATION OF RATE

Date	Dial Error + = Fast - = Slow		Daily Rate + = Gain - = Loss	Mean Deviation in Daily Rate	Remarks
	Min	Sec			
Oct 1948					
3	+0	2			Started + Set
4	+0	2 1/2	+ 1/2		
5	+0	2 1/2	0	1/4	
6	+0	3	+ 1/2	1/4	
7	+0	3	0	1/4	
8	+0	3 1/2	+ 1/2	1/4	
9	—	—	—	—	Not wound
10	+0	4	+ 1/4	—	2 day avg.

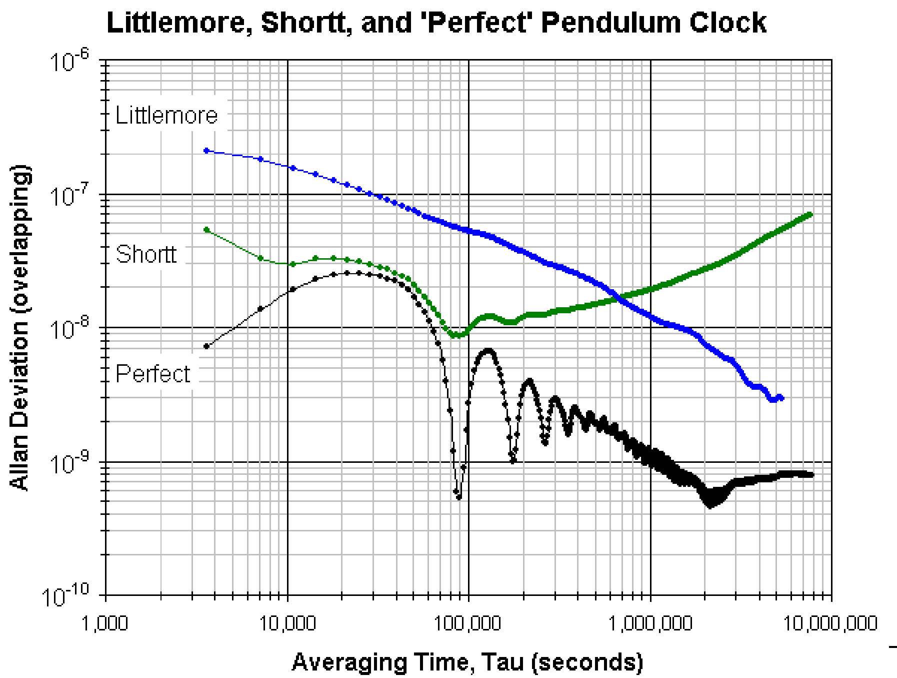
(Mean daily rate = +1/4 second)

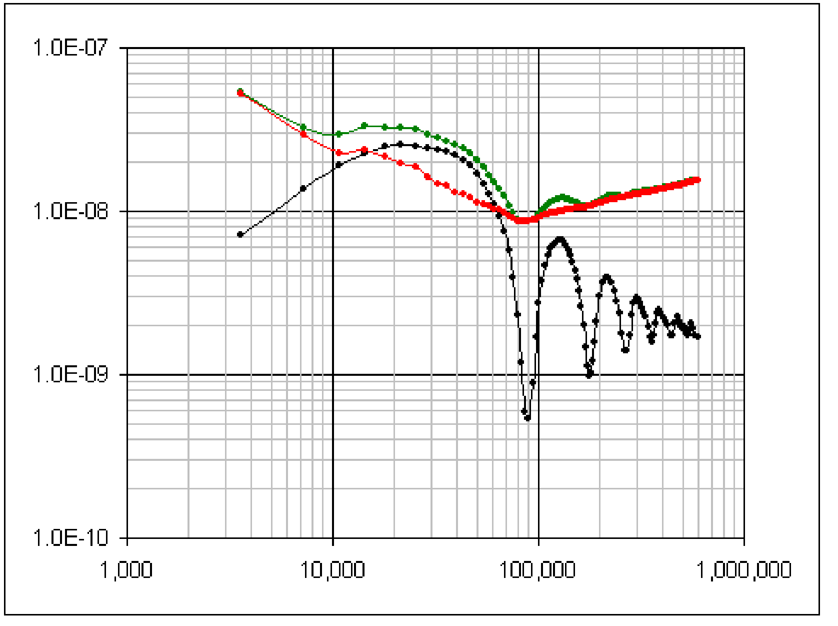
In Table I, there will be noted a column headed "Mean Deviation in Daily Rate." The

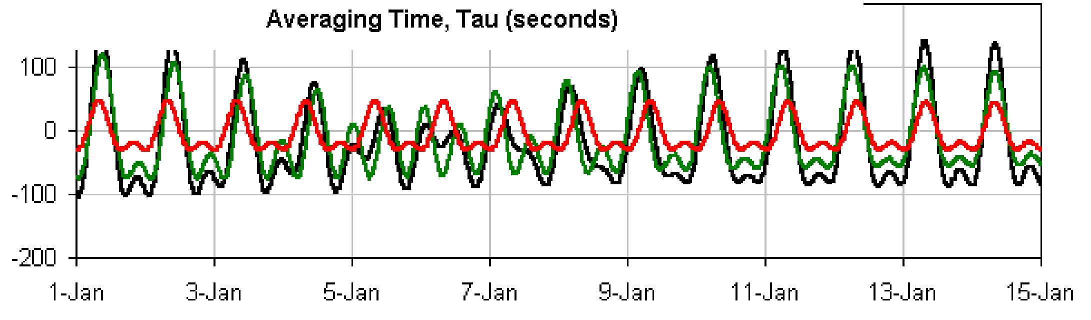
10^{-8} pendulum clock

- 0.01 ppm, 10 ppb
  10 ns/s, 864 µs/d
- Shortt,
  Fedchenko,
  Riefler,
  ‘Littlemore’

10^{-8} pendulum clock



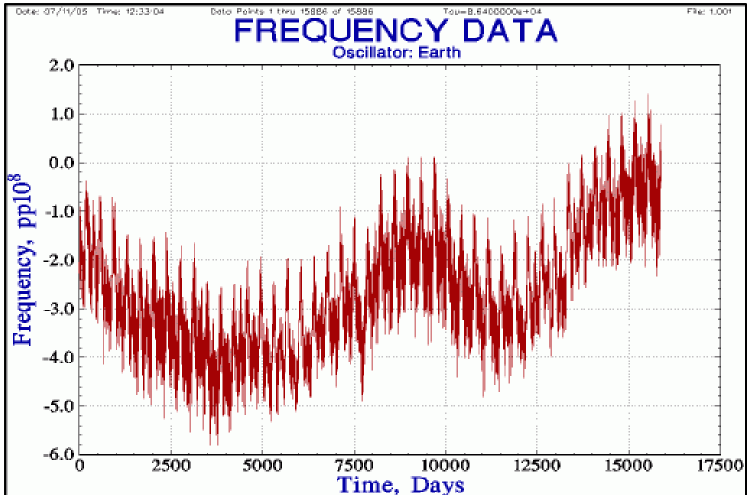


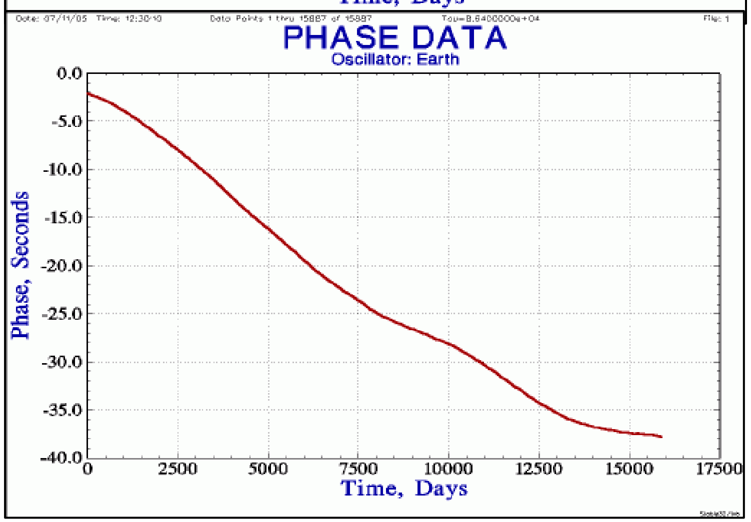


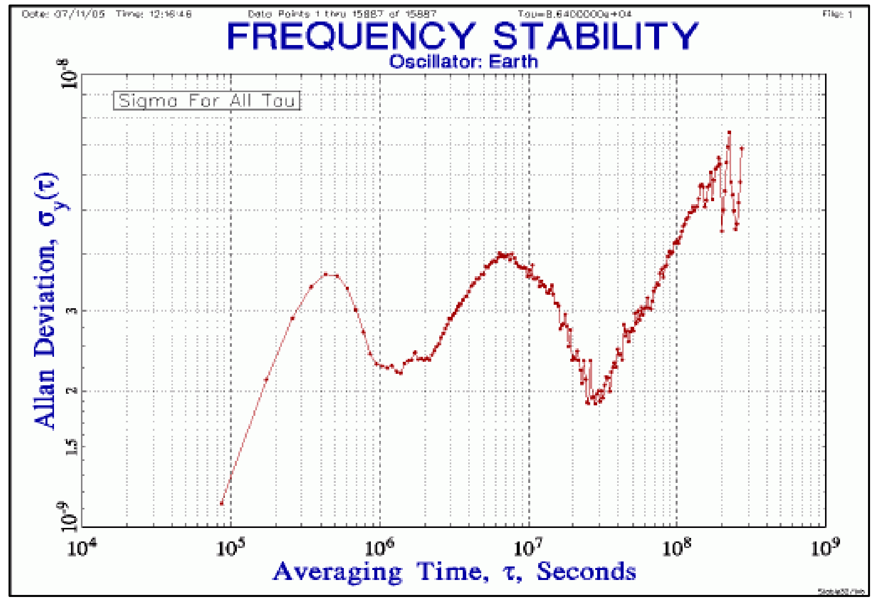
10^{-9} earth

- 0.001 ppm
- Slow by ~2 ms per day
- Also somewhat irregular
- ADEV $10^{-8} \sim 10^{-9}$
- Limited by core, weather, climate
- Lunar/solar tides, periodic variations
- Tidal friction, long-term drift

10^{-9} earth (40y of data)

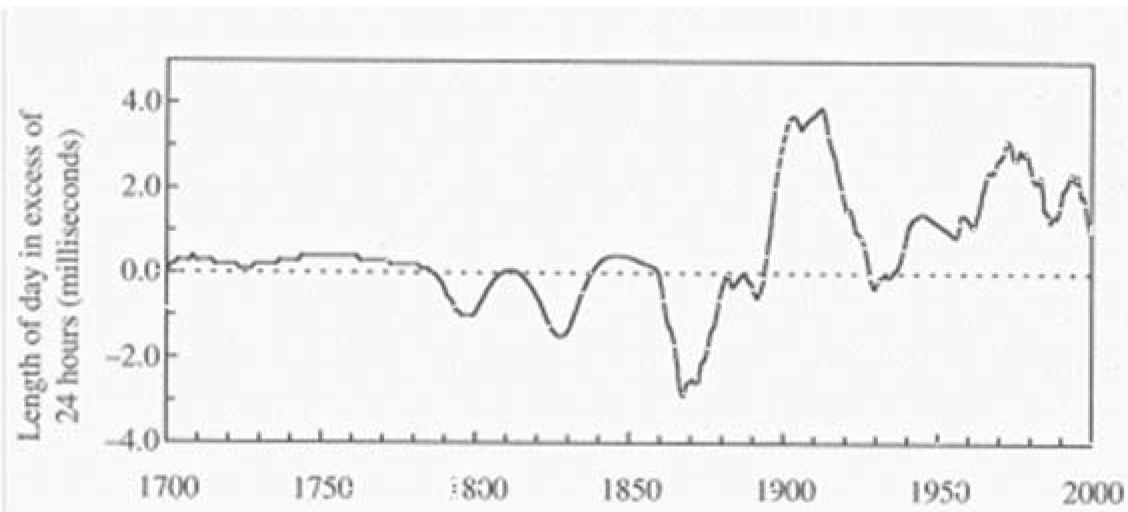






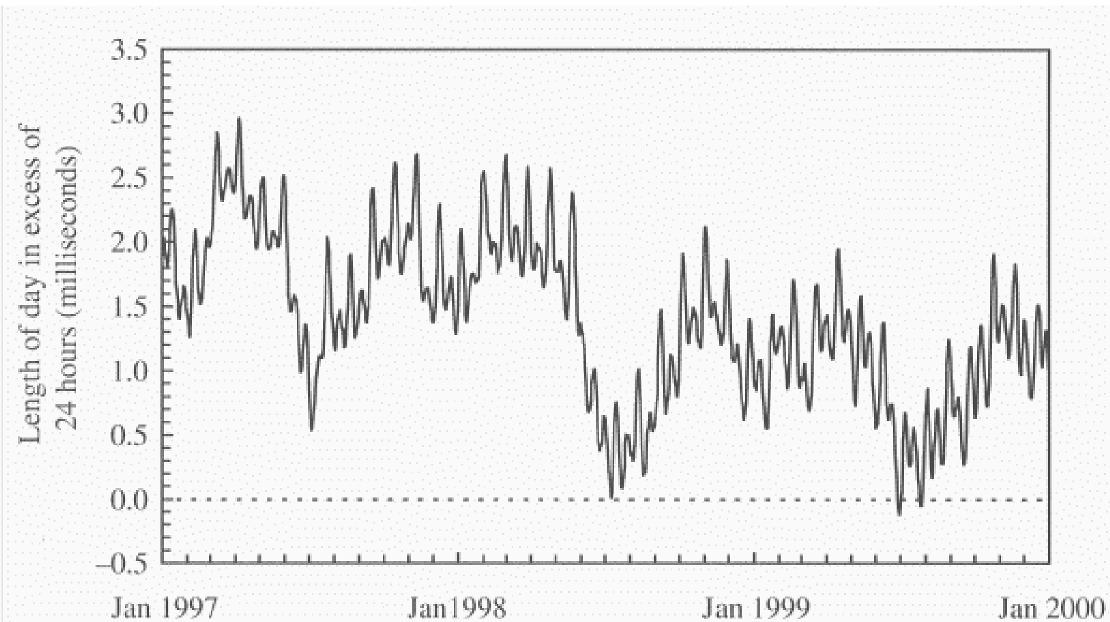
10^{-9} earth clock

- Long-term plot (300 years)
- Length of day (LOD) is 86,400 seconds ± a few milliseconds

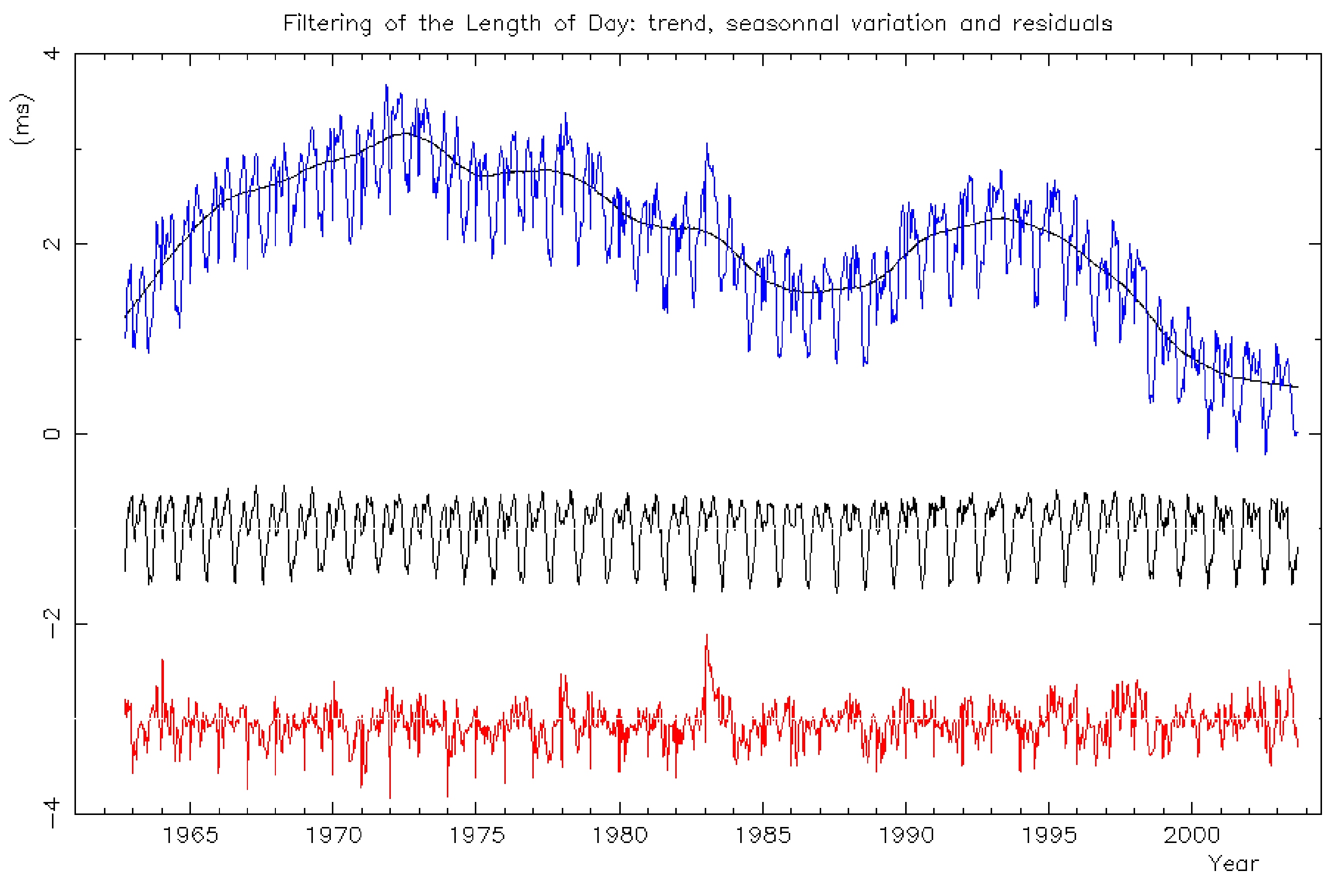


10^{-9} earth clock

- Short-term plot (3 recent years)
- LOD is about 86,400.002 seconds



10^{-9} earth clock

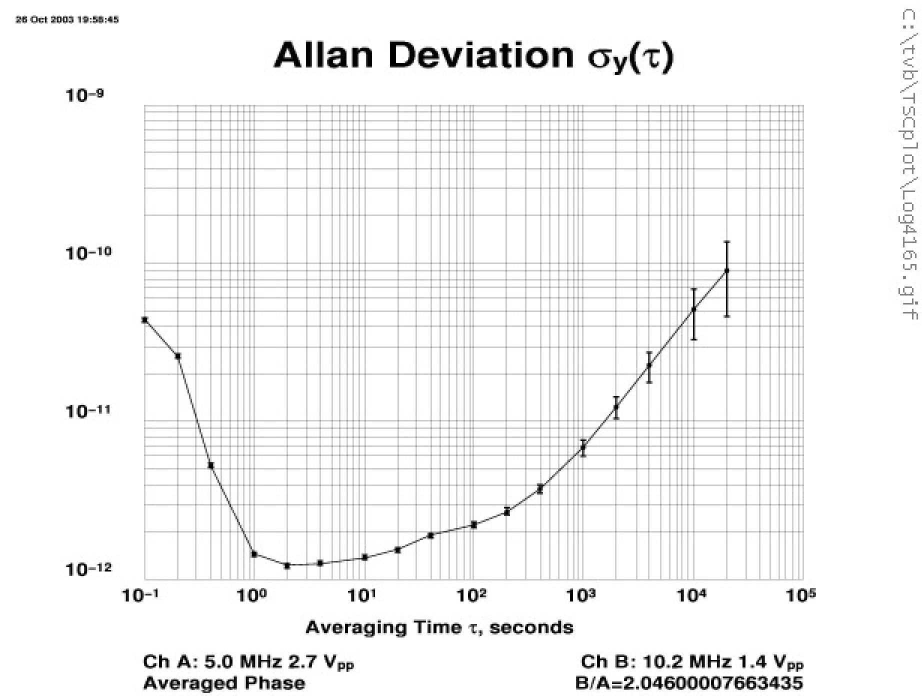


10^{-9} earth frequency standard

- Suggested improvements:
  - Thoroughly clean, and dry with cloth
  - Remove surrounding gas and water vapor
  - Wait for core to cool before use
  - Re-align axis of rotation (wobbling)
  - Keep away from nearby moon (tides)
  - Keep away from sun (tempco)
  - Re-adjust rate (avoid leap seconds)

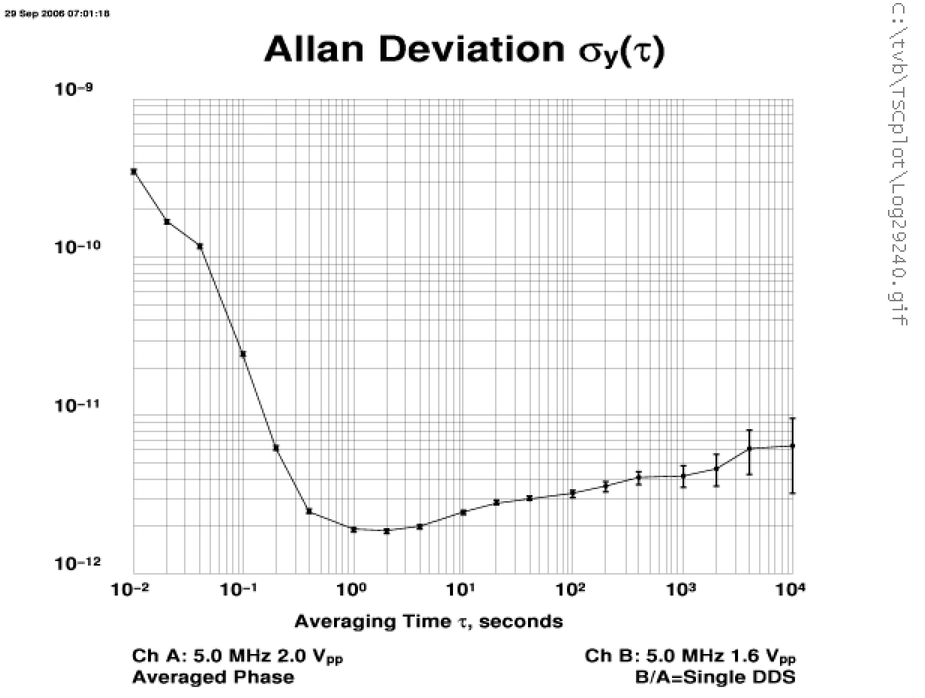
10^{-10} ocxo

- 0.1 ppb, 100 ps/s, 8.64 µs/d
- 10^{-10}…10^{-13} short
- 5×10^{-10}/d drift



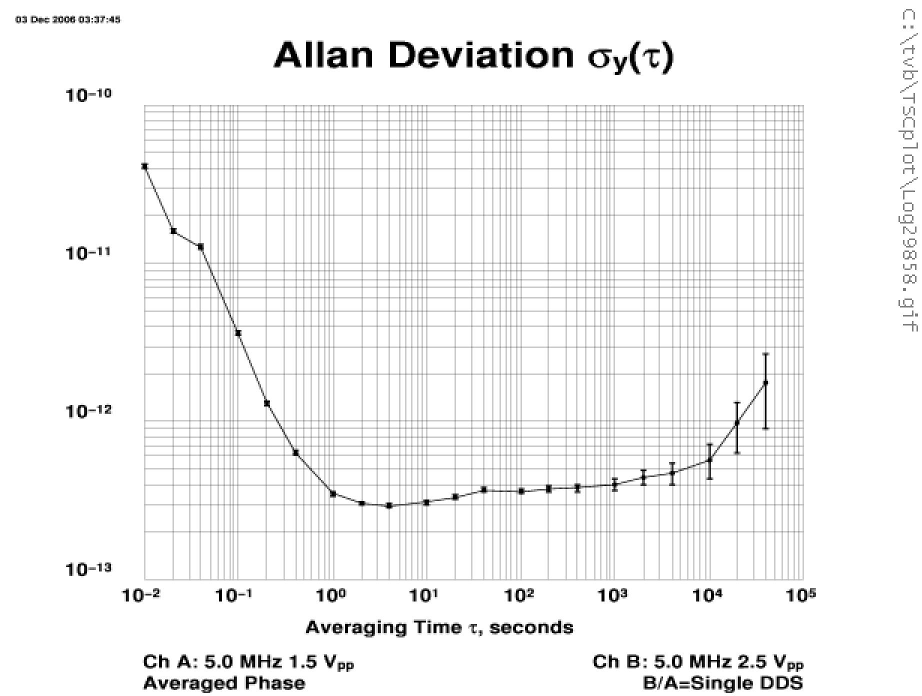
10^{-11} good ocxo

- 0.01 ppb, 10 ps/s, 864 ns/d (~1 µs/d)
- $10^{-11} \ldots 10^{-13}$ short
- ~10^{-11}/d drift



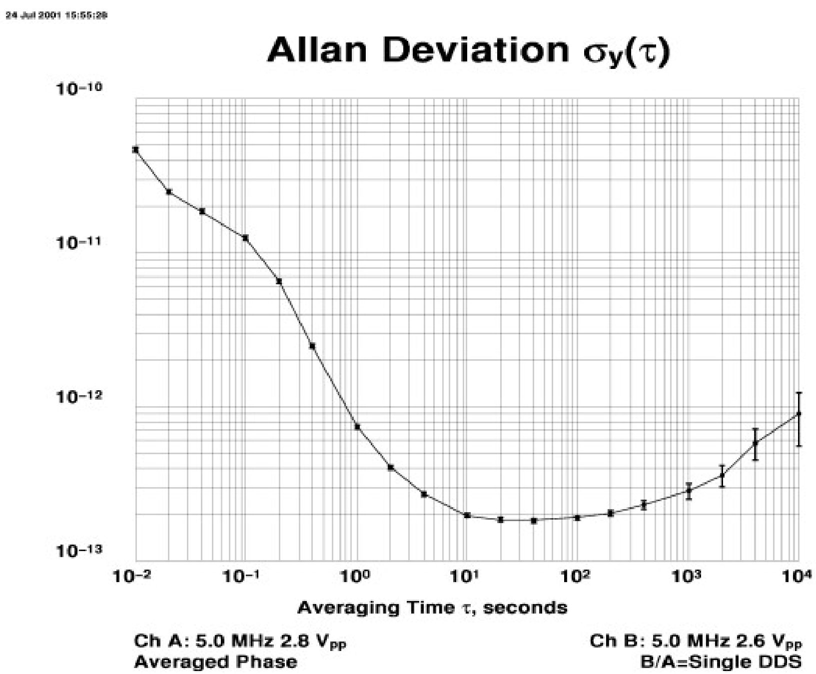
10^{-12} excellent ocxo

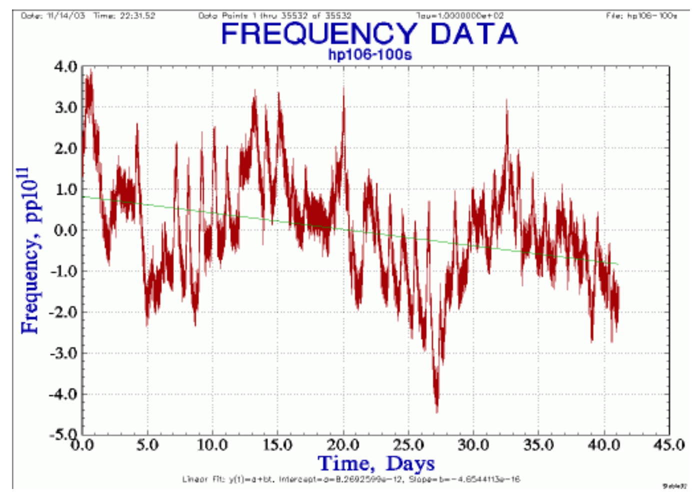
- 1 ppt, 1 ps/s, 86.4 ns/d (~100 ns/d)
- ~10^{-13} short/mid
- ~3×10^{-12}/d drift



10^{-13} hp 106B quartz

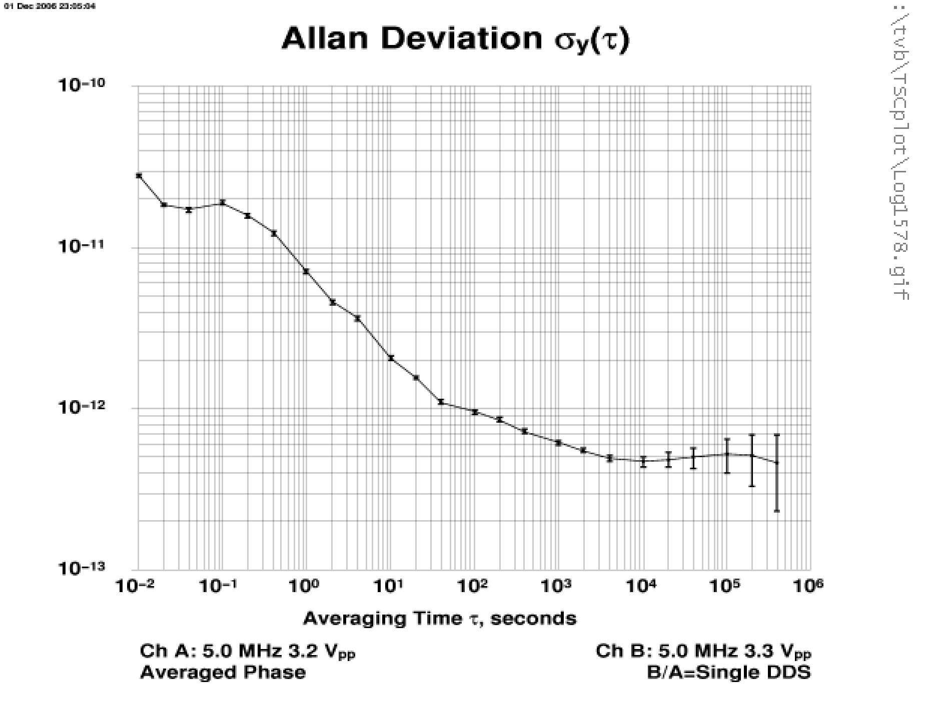
- Best hp quartz
- ~4×10^{-13}/d drift





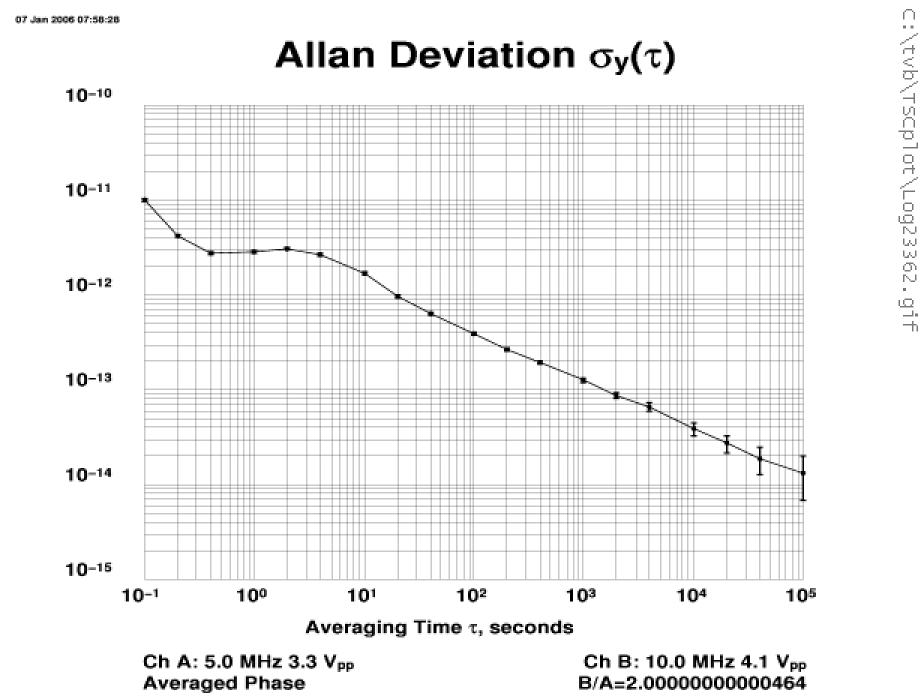
10^{-13} rubidium

- 8.64 ns/d (~10 ns/d)
- ~10^{-13} mid-term
- ~1×10^{-11}/m drift



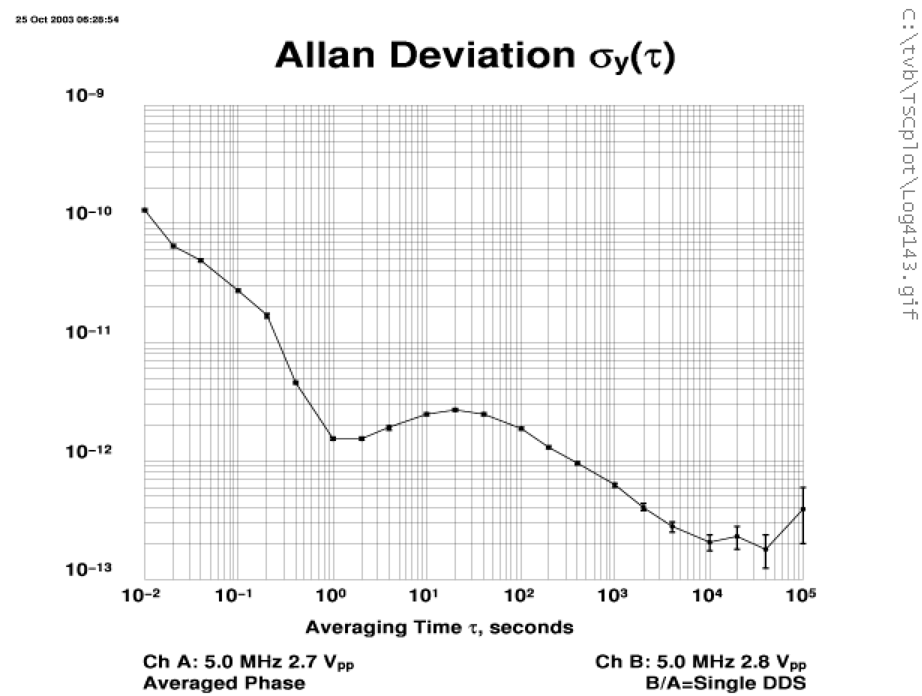
10^{-14} cesium

- 864 ps/d (~1 ns/d)
- ~10^{-13} mid-term
- ~1×10^{-14} @ 1 day



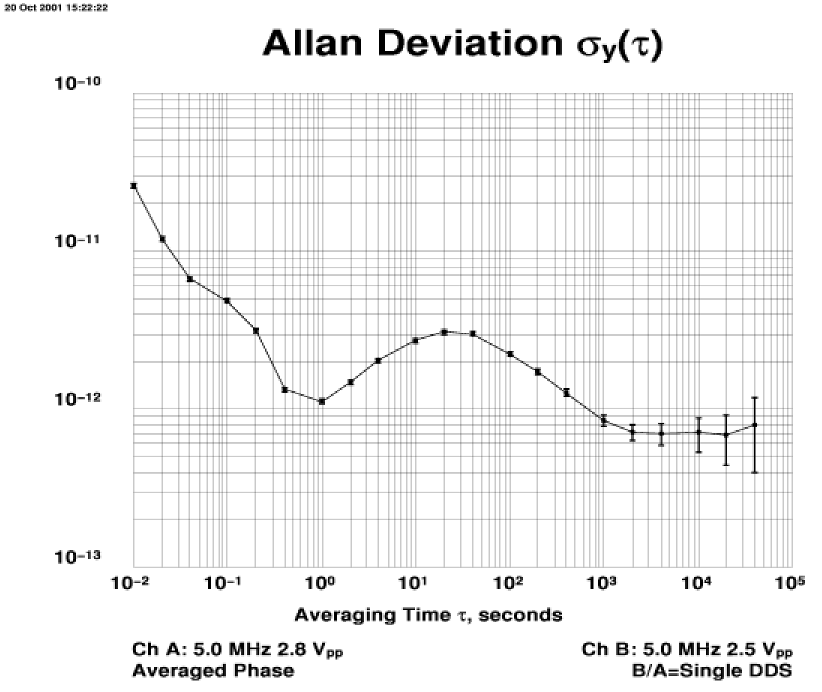
10^{-14} more cesium

- 10^{-14} not!
- Cesium clocks differ by 2x – 50x
- Vintage 5060A



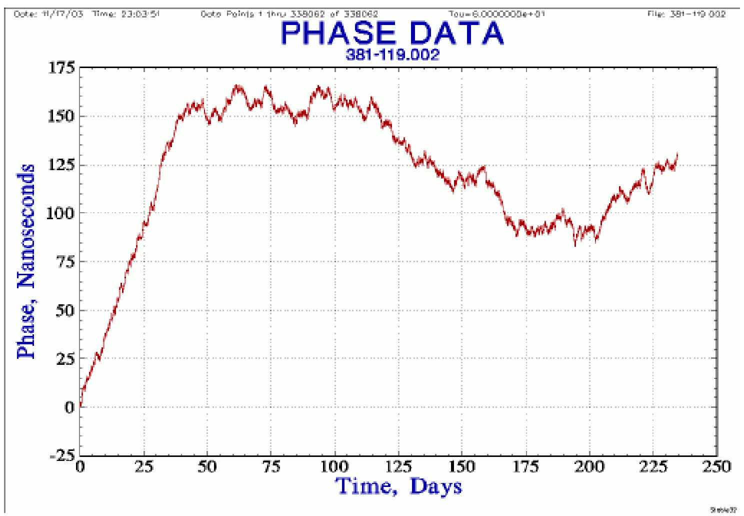
10^{-14} another cesium

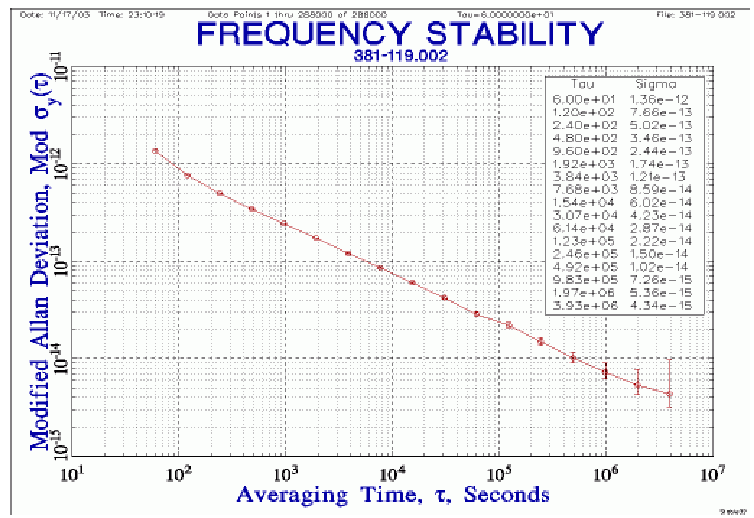
- Not even close to 10^{-14} @ 1 day
- FTS 4010
- Portable clock



10^{-15} hp 5071A cesium

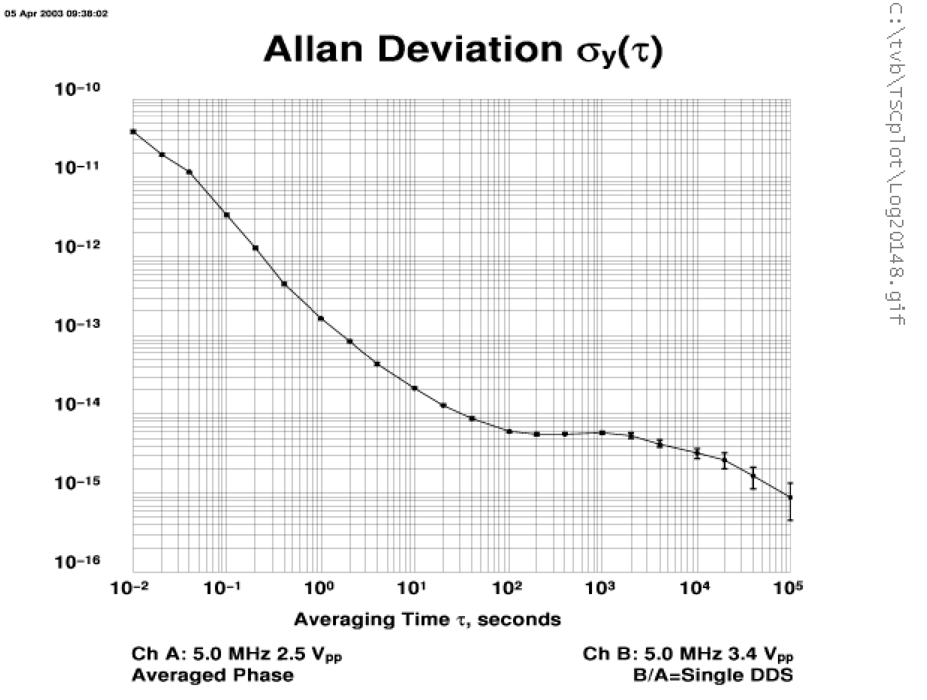
- High-performance model
- Pair ~2×10^{-14} at a day
- Flicker floor ~5×10^{-15} in weeks





10^{-16} active h-maser

- 8.64 ps/d
- Under 1×10^{-15} @1d
- Most stable



Summary – powers of ten

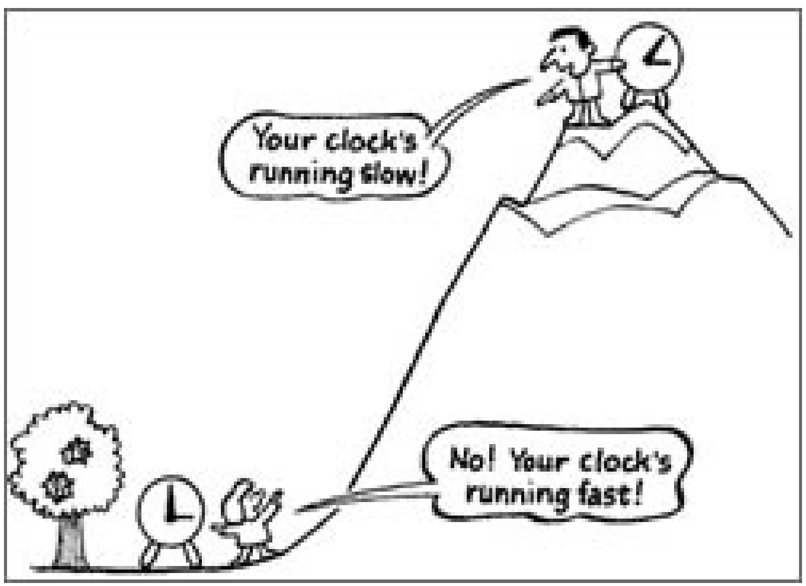
- 17 orders of magnitude
- From a billion times worse than earth or a pendulum clock
- To a billion times better than earth or a pendulum clock

4. kids, clocks, and relativity

- What to do with atomic clock hobby?
- Einstein said time itself is not fixed
  - S.R. predicts *higher speed* slows time
  - G.R. predicts *stronger gravity* slows time
- Is this only abstract theory in textbooks?
  - fast moving rocket ships and twins
  - objects getting too close to black holes
- Can this be tested for real on earth?

Relativity at home

- We have many atomic clocks at home
- No planes or rockets (high speed)
- But we have mountains (high altitude)



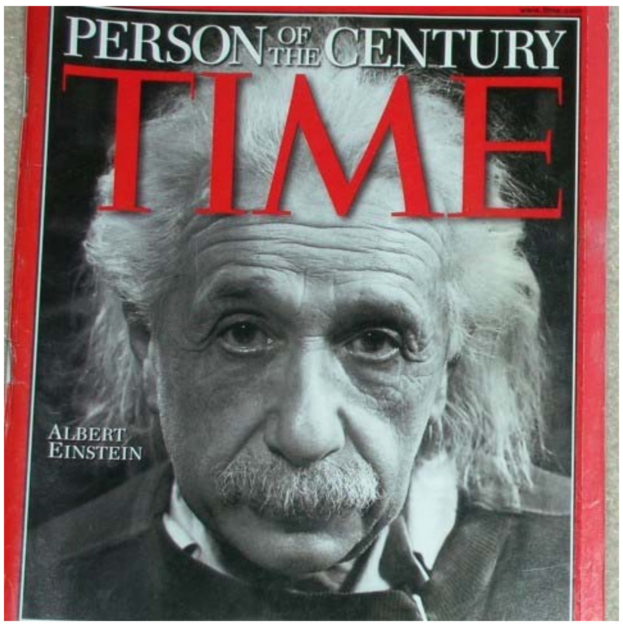
From NPL website

Big idea

- Take our 3 kids with *portable* cesium clocks high up Mt Rainier
- See if Einstein was right about *gravity* and *time*
- See if clocks really run *faster* up there

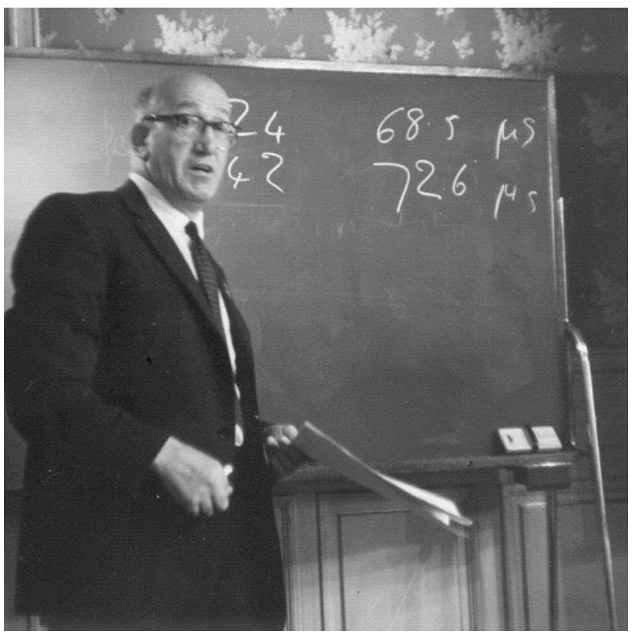
Einstein and 2005

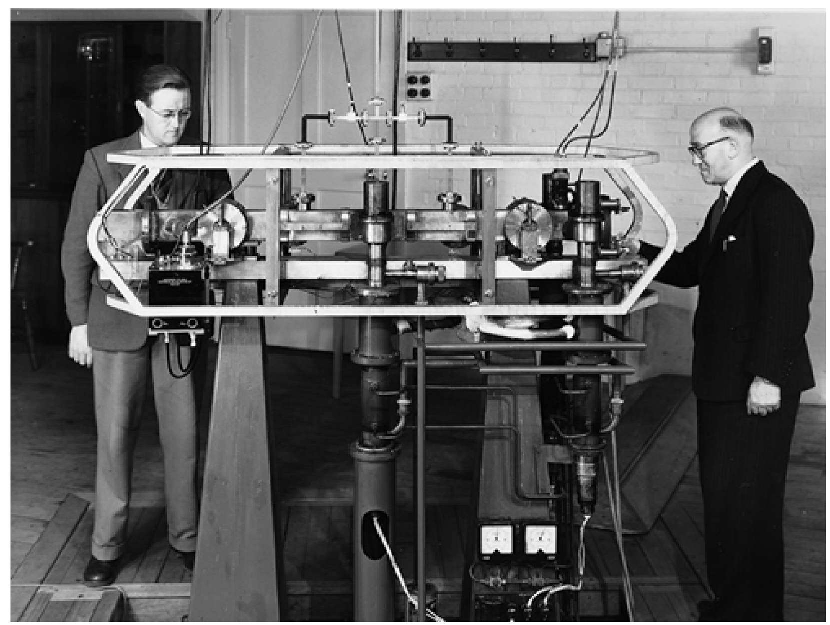
- 100^{th} anniversary of relativity: books, magazines, radio, TV, web sites, "Physics Year", lectures…



Louis Essen (UK) and 2005

- 50th anniversary of *cesium* clock (NPL)
- "famous for a second" 9 192 631 770 Hz





Project GRE²AT

- General Relativity Einstein/Essen Anniversary Test (2005)
  - 100th anniversary (Einstein) theory of relativity
  - 50th anniversary (Essen) first cesium clock
- Combine atomic clock hobby, physics, history, technology, math, computers, children, car trip, vacation, and family fun

Clock equations

$$d\tau' = \frac{d\tau}{\sqrt{1-\frac{v^2}{c^2}}}$$

- To a first approximation, small v, small h
- Kinematic: $\Delta f_k \approx -\frac{1}{2}v^2/c^2$
- Gravitation: $\Delta f_g \approx +gh/c^2$
- Sagnac: $\Delta f_s \approx -\omega R^2\cos^2(\phi)\bullet\lambda \,/\, c^2$
- Net freq $\Delta f = \Delta f_k + \Delta f_g + \Delta f_s$
- Total time $\Delta T = \sum \Delta f \times T$
- These corrections are usually *infinitesimal*

Magnify the effect

- Go as **high** as possible
- Stay as **long** as possible
- Measure as **precisely** as possible

Cartoon by Dusan Petricic
Scientific American column Wonders by Philip and Phyllis Morrison
http://www.sciam.com/1998/0298issue/0298wonders.html

Time dilation calculation

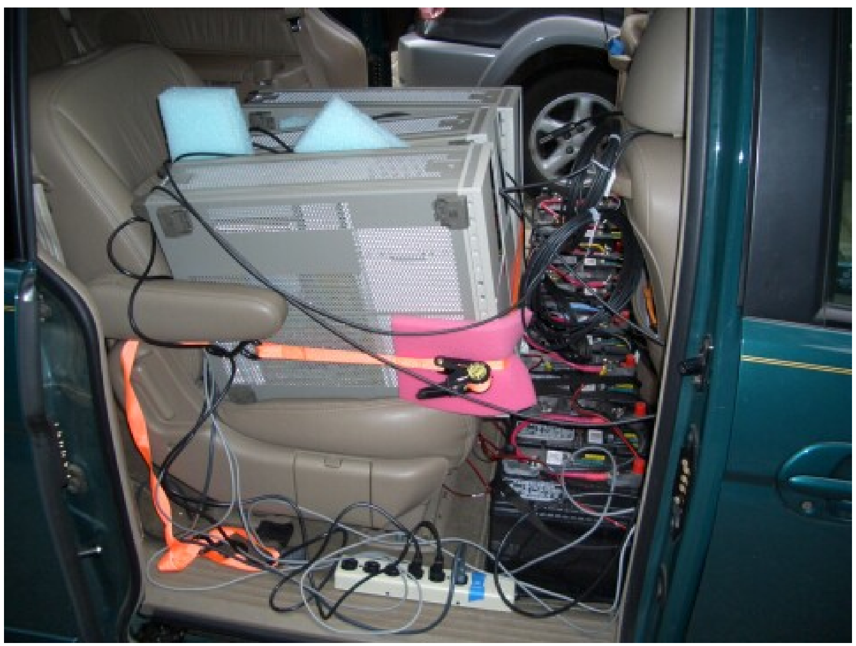
- Turn *infinitesimal* into *measurable*
- Frequency change $\Delta f \approx gh/c^2$
  $\Delta f \approx 1.09\times10^{-16}$ s/s/meter
- But if you go up 1 km instead of 1 m, then
  $\Delta f = 1.1\times10^{-13} = 0.11$ ps/s
- And if you stay up there 24 hours, then
  $\Delta T = \Delta f \times 86400\ s = 9.5\times10^{-9}\ s = 9.5$ ns
- Gravitational time dilation $\approx$10 ns/day/km

The GREAT trip, day 1

- Carrying clock downstairs. Limited time; car is a mess, but it works.

The GREAT trip, day 1

- Clocks in the middle, batteries on the floor, and instrumentation in the front.



The GREAT trip, day 1

- Kids in the back. Dad making final clock BNC connections; Mom says goodbye.

The GREAT trip, day 1

- Detail of TIC's and laptop in front seat and clocks in middle seat. 23:33:48 UTC

The GREAT trip, day 1

- Final gas stop and evening arrival at Rainier National Park.

The GREAT trip, day 2

- Paradise Inn is at 5400’ elevation. Large parking lot to hide in.

The GREAT trip, day 2

- Classic old Northwest inn; you should visit sometime.

The GREAT trip, day 2

- Wonderful hiking trails and climbing. Lucky to have clear weather.

The GREAT trip, day 2

- Avoid a ticket and move the car again. Ouch, running low in fuel. Now what.

The GREAT trip, day 3

- Got gas at 6 AM. Used 15.78 gal in 34 h = 0.46 gph; ~2h/gal, so about 1 ns/gal.

The GREAT trip, day 3

- More hiking, exploring, playing. It's a fun place for a while.

The GREAT trip, day 3

- 42 hours is up; time to leave. We're all tired. Can this really work? Go home.

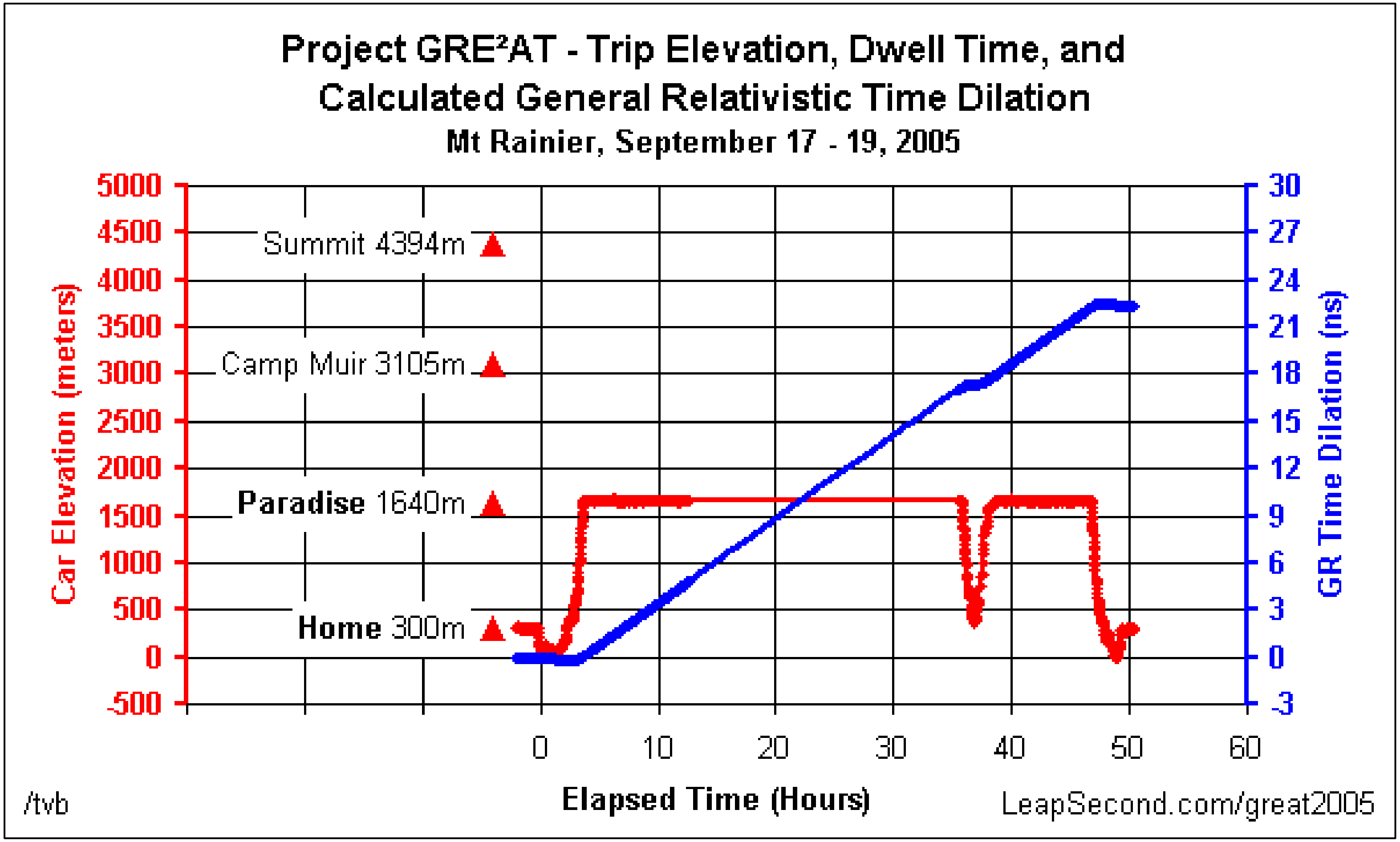
The GREAT trip

- Home clock and mountain clock elevations

Two questions

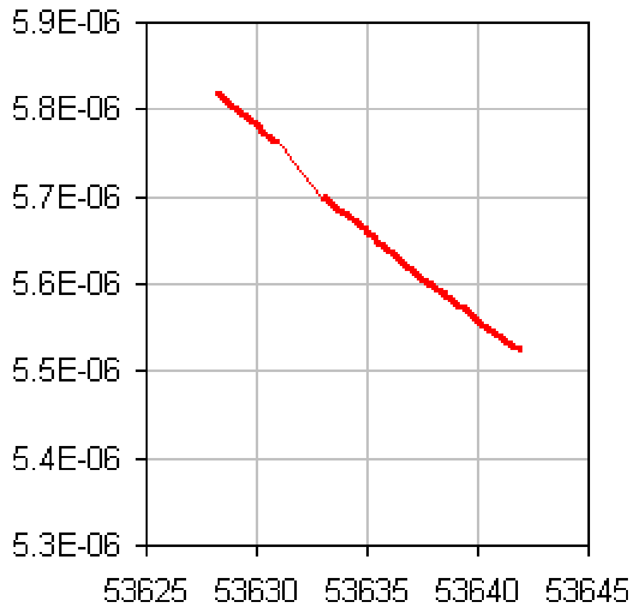
- Results are unknowable until the return
- (1) Did we see any time dilation?
  - requires before/after time-rate comparison
  - comparison against stable “house” clock
- (2) Did the results match prediction?
  - requires record of altitude and duration
  - used Garmin GPS NMEA log

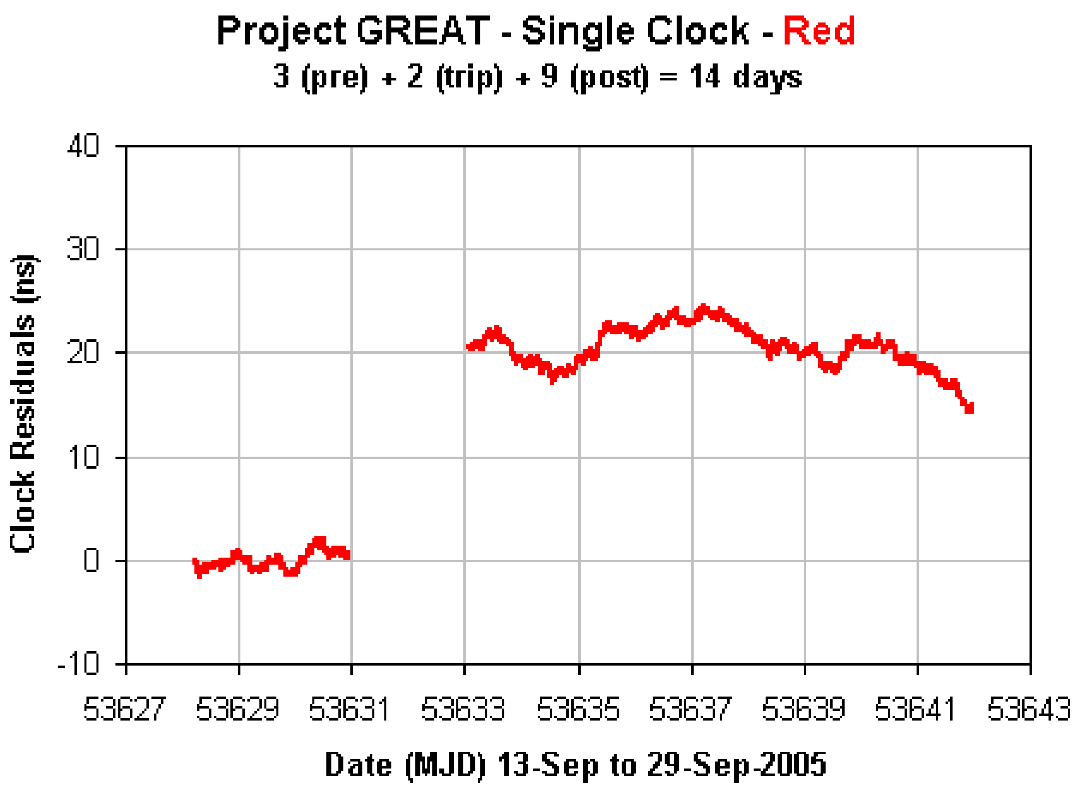
Elevation and *predicted* dilation



Clock results *(measured)*

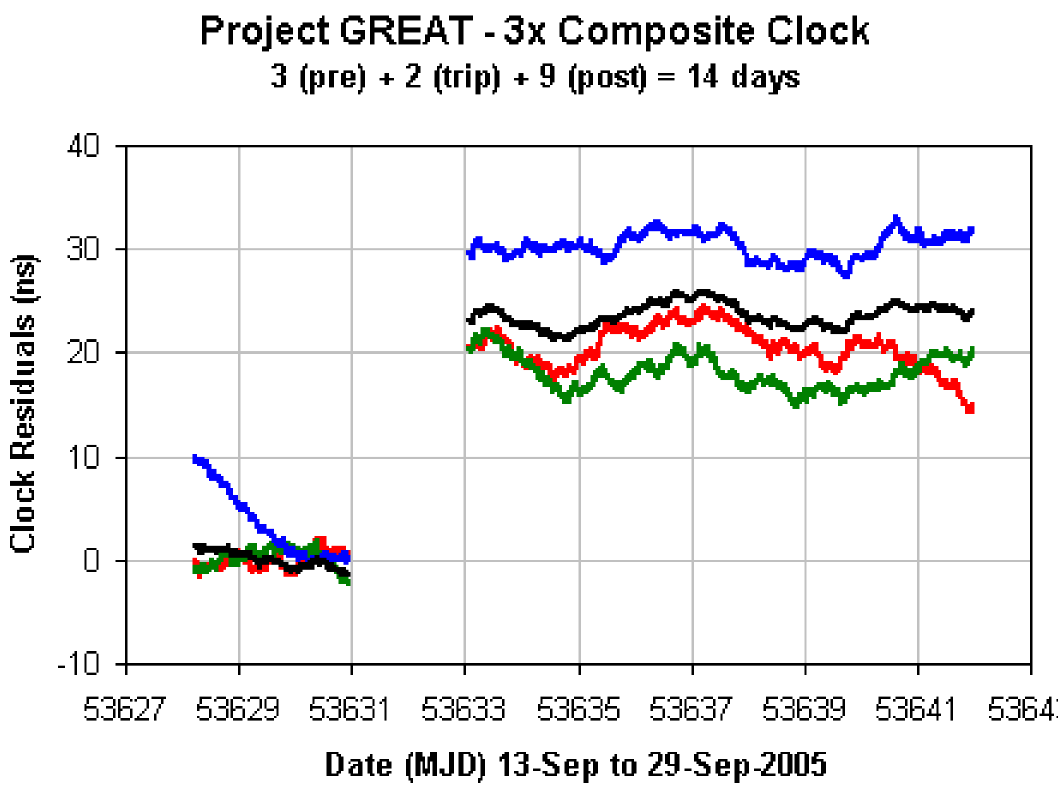
- Red
  20.3 ns





Mean clock results

- Mean
  23.2 ns
- ±4 ns
- Predict
  22.4 ns



GRE²AT experiment worked

- Time dilation is real!
  - gravitational effect (elevation, *not* velocity)
  - we came back 22 ns older and wiser
- As astronomer Steve Allen observed:
  - *”relativity is now child’s play”*
- Unexpected press
  - Physics Today, WIRED magazine
- “Best atomic clock is a good gravimeter”

5. conclusion

- A quick view of extreme timekeeping
- Electronics is not as elegant as Harrison, Tompion, or astronomical pendulum clocks of 18th and 19th century
- Perhaps 20th and 21st century laboratory clocks will get their place in history too
- Clockmaker motivation is the same
- “Origins, evolution, future of public time”

Thanks for your time

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