Passion and Precision: *Adventures of a Time-Nut*

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About *tvb*

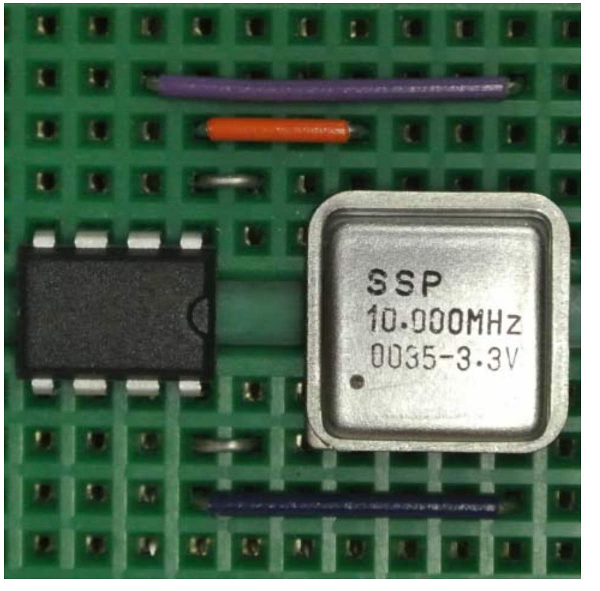
- Tom Van Baak (Bellevue, WA)
- Education: math, physics, computers
- Profession: software engineer (kernel)
- Passion: electronics, technology, precise time & frequency

Outline

- 0 Introduction to T&F
- 1 The best clock
- 2 Powers of ten
- 3 GREAT adventure

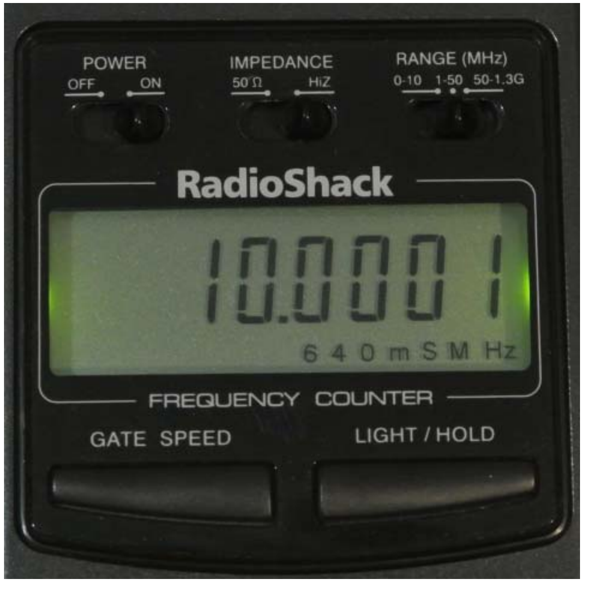
Time & Frequency hobby

- 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)

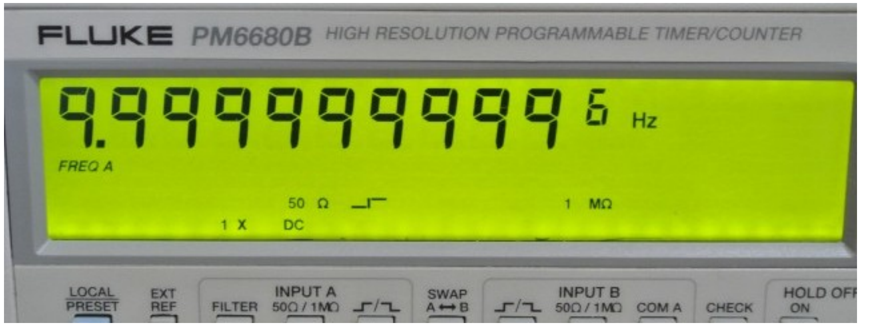


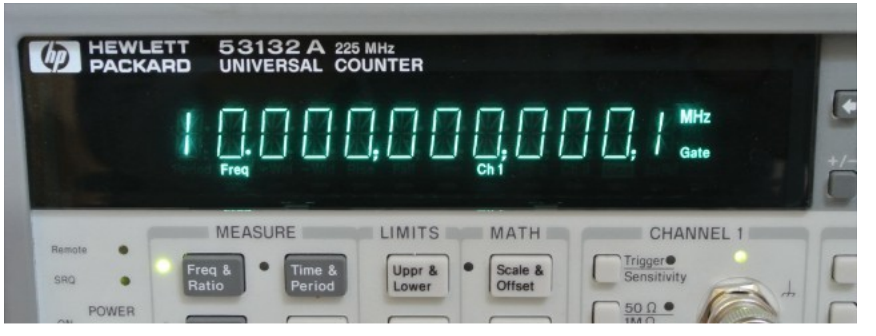
More accuracy

- 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?
  – how does WWVB work; or GPS?
  – 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
  - anything about precise time & frequency
- Help! I've got the *"time bug"*

Home time lab

- So now I have quite the time lab
- Mostly used test equipment (eBay)
- Old boat-anchors (fascinating, historical)
- Oscillators, frequency counters, phase comparators, phase noise analyzers
- WWV, WWVB, GPS receivers, GPSDO
- TCG, IRIG displays, nixie clocks, *hp*

Home time & frequency lab

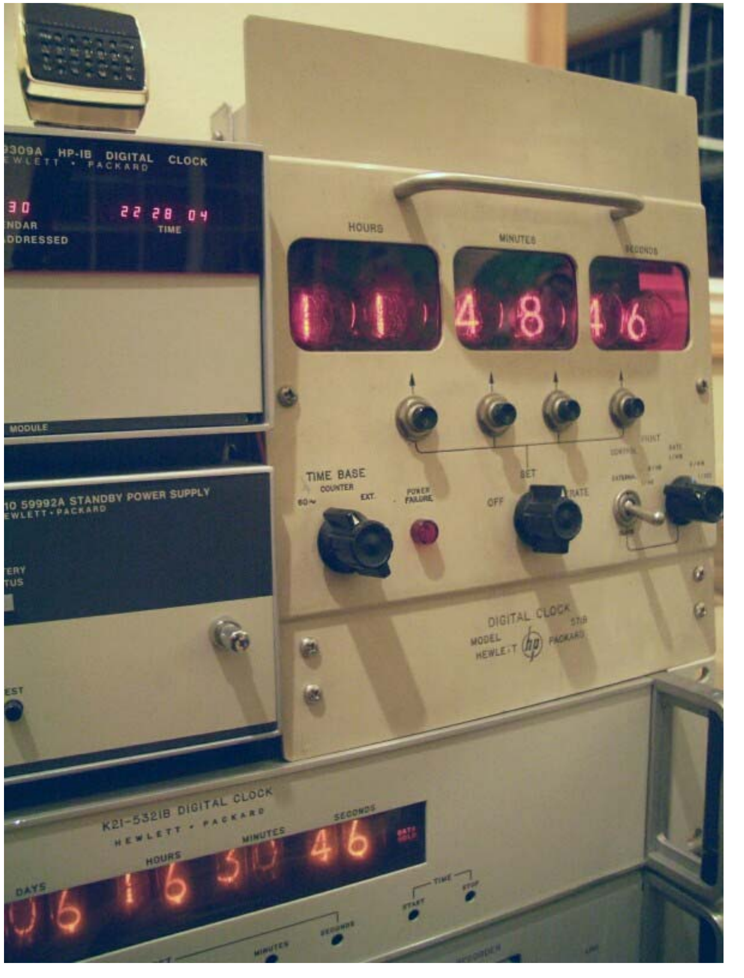
Museum of *hp* clocks

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 natural, stable Cs_{133} atoms, not the scary man-made *radioisotope* Cs_{137}
- Analogy: C_{12} vs. C_{14}
- "hyperfine" transition
- 9,192,631,770 Hz
- Solid / liquid metal

Hobby status

- House full of time & frequency gear
  - high-precision experiments now easy to do
  - I help amateur friends, world-wide
- Most modern technology depends on:
  - precise *time* synchronization
  - stable *frequency* references
- The T&F niche is deep and fascinating
  - reading, collecting, experimenting, sharing

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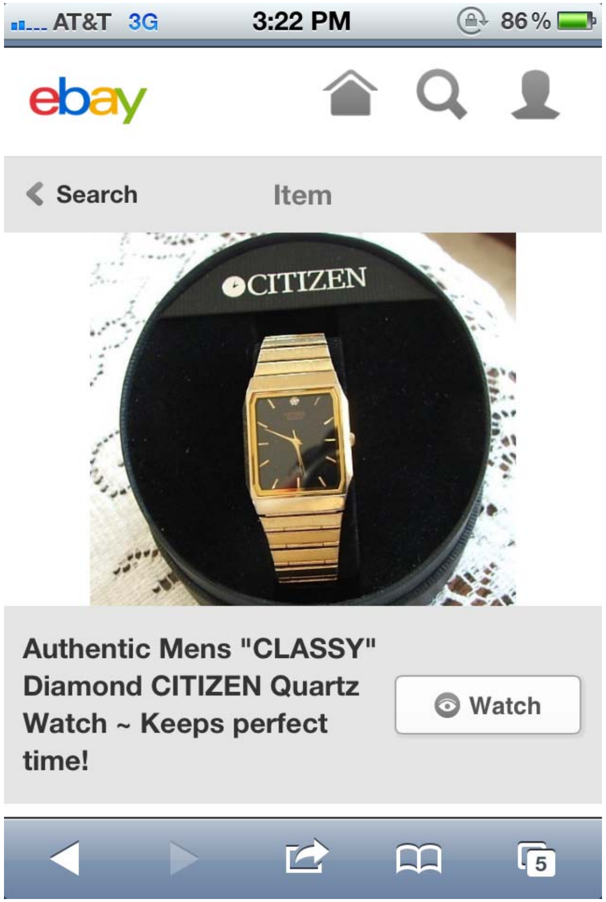
What is the *best* clock?

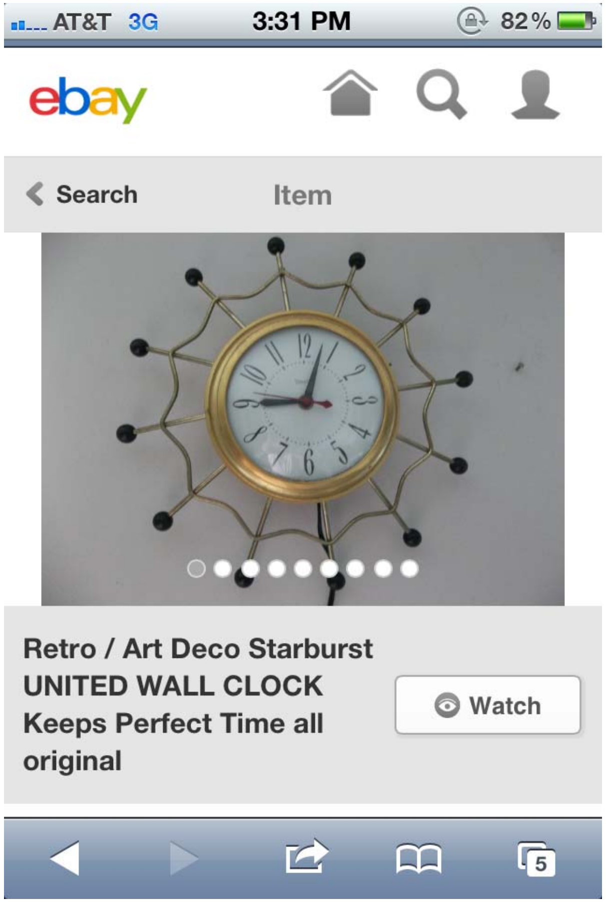
- Best for timekeeping?
- Or other considerations:
  - size, operating voltage, power, price
  - jitter, phase noise, Allan deviation, drift
  - lifetime, reliability, harsh environments
  - temperature, humidity, pressure, acceleration
  - auto-, medical-, mil-, space-qualified
  - rack-mount or portable

Is there a best timekeeper?

- 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 math correction
  - then you have the best watch

Best wristwatch

Measurement

- The more stable the clock, the more precise the measurement needs to be
- Two oscillators are *never* identical:
  - are you looking close enough?
  - or, are you waiting long enough?
- Compare clocks
  - measure frequency directly, or
  - measure slow phase drift between oscillators

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
  - measure of frequency instability (*sigma*)
  - as a function of sampling times (*tau*)
- prediction of clock stability in future (past)

Collect, measure, experiment

- No end to time & frequency experiments
- Oscillator phase noise measurements
- Accuracy, stability, long-term drift rates
- Measure frequency counter resolution
- Test WWVB, GPS receivers, GPSDO
- Try clock ensembles, your own UTC
- Write lab reports, share with others

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Powers of ten – introduction

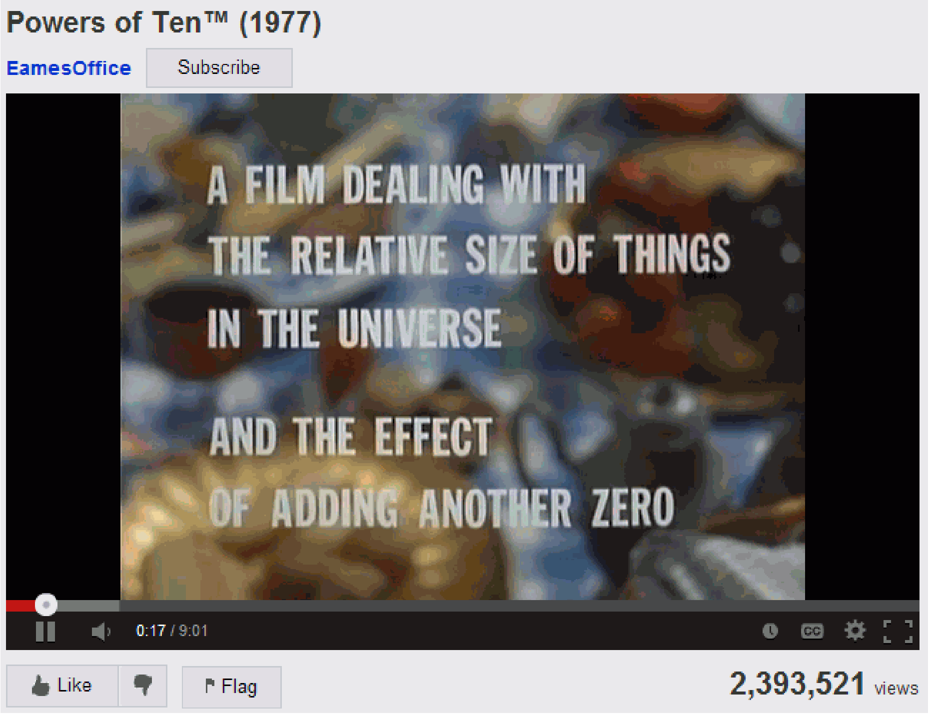
- Not all clocks are super accurate
- <u>Any</u> periodic event can be a clock
- How *regular* the occurrence determines how *good* or *bad* the clock is
- The range of precision/stability is huge

Fractional units

- 1 second / day = ~1.2×10^{-5}
- 3 seconds / month = 10^{-6} = 1 ppm
- 1 second / month = ~3.8×10^{-7}
- 1 second / year = ~3.2×10^{-8}
- 1 ms [***milli***second] / day = ~10^{-8}
- 1 µs [***micro***second] / day = ~10^{-11}
- 1 ns [***nano***second] / day = ~10^{-14}
- 1 second / 3,000,000 years = ~10^{-14}

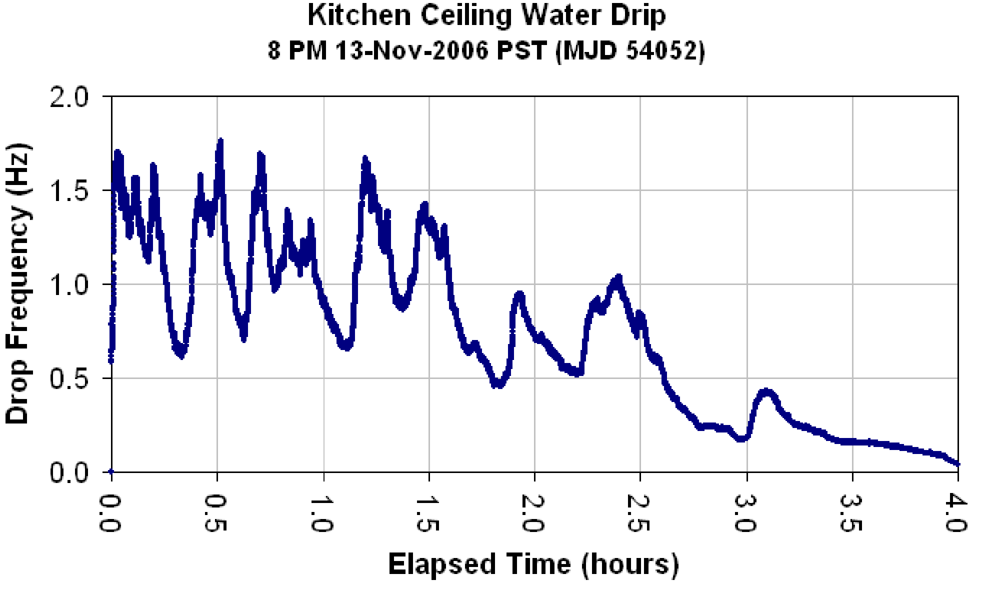
"Powers of Ten" – inspiration

- Charles and Ray Eames (1977)
  - "the effect of adding another zero"

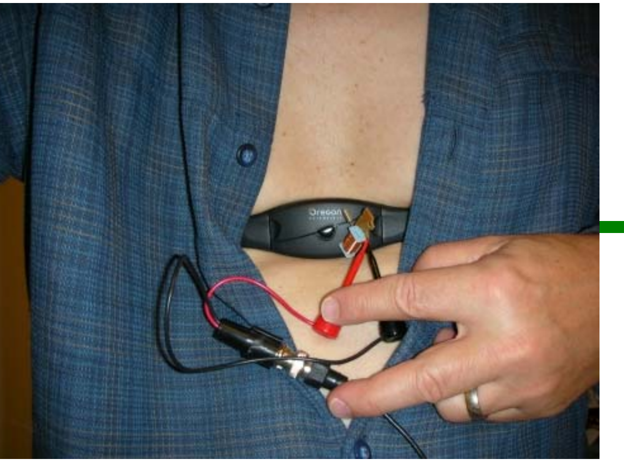


10^{-0} drip, drip

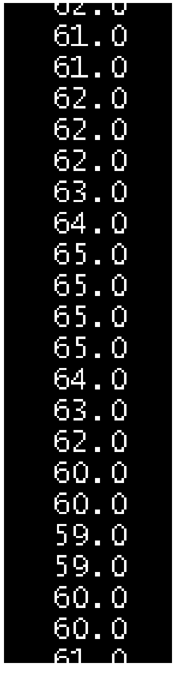
- Leak in ceiling
- 0.57 s … 9.9 s
- 1.7 Hz … 0.1 Hz



10^{-1} heart beat

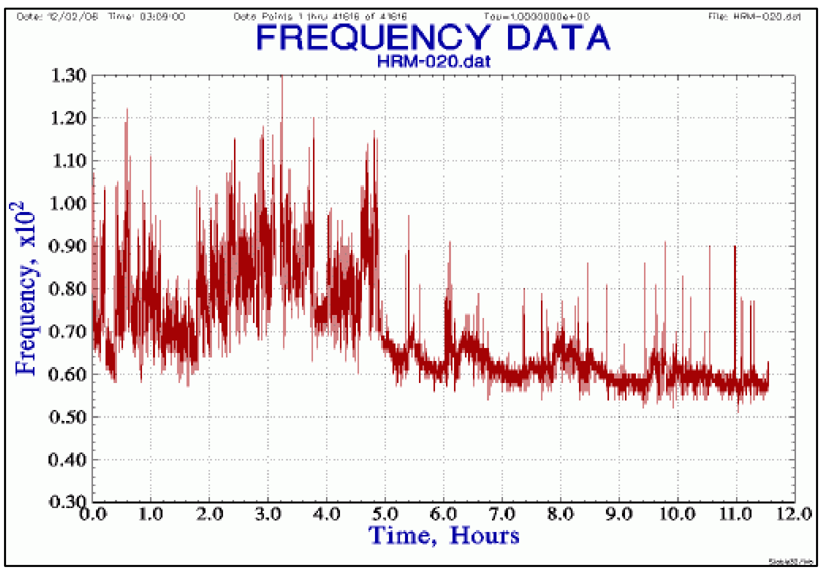


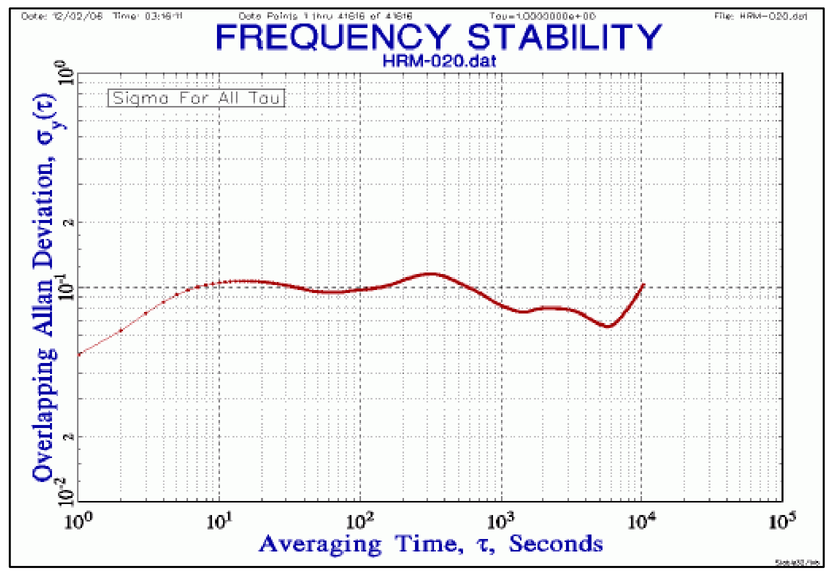
- 10^{-1}, 0.1, 10%
- The original ‘1 PPS’
- Sometimes 2x, even 3x
- Much higher stability at night
- < 10% accuracy possible



10^{-1} heart beat

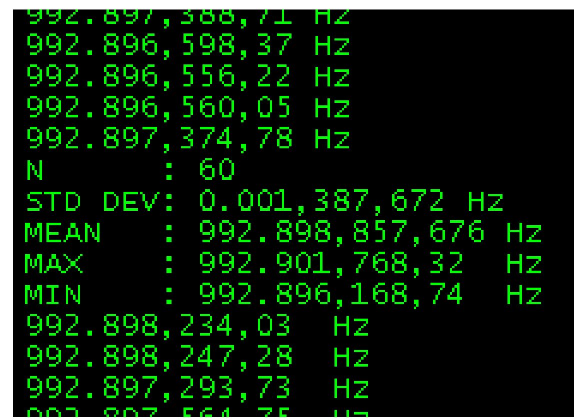
- 12 h frequency plot (evening/night)
- ADEV floor is 10^{-1} from 10^1 to 10^4 s!
- (is this OK?)



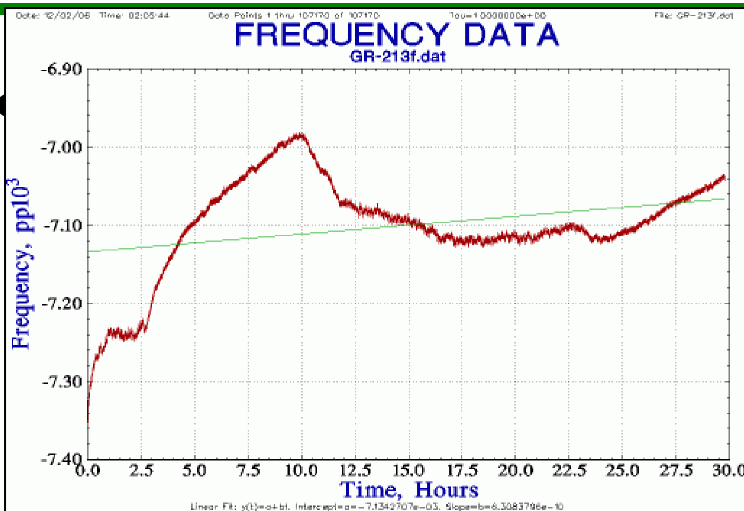


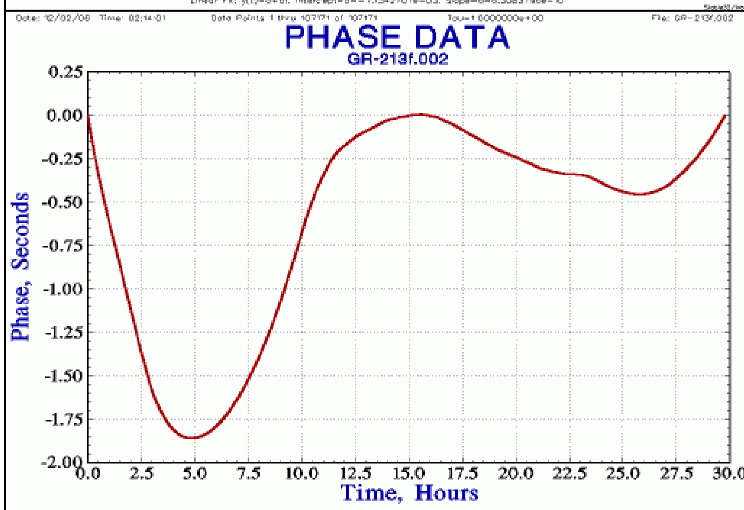
10^{-2} tuning fork oscillator

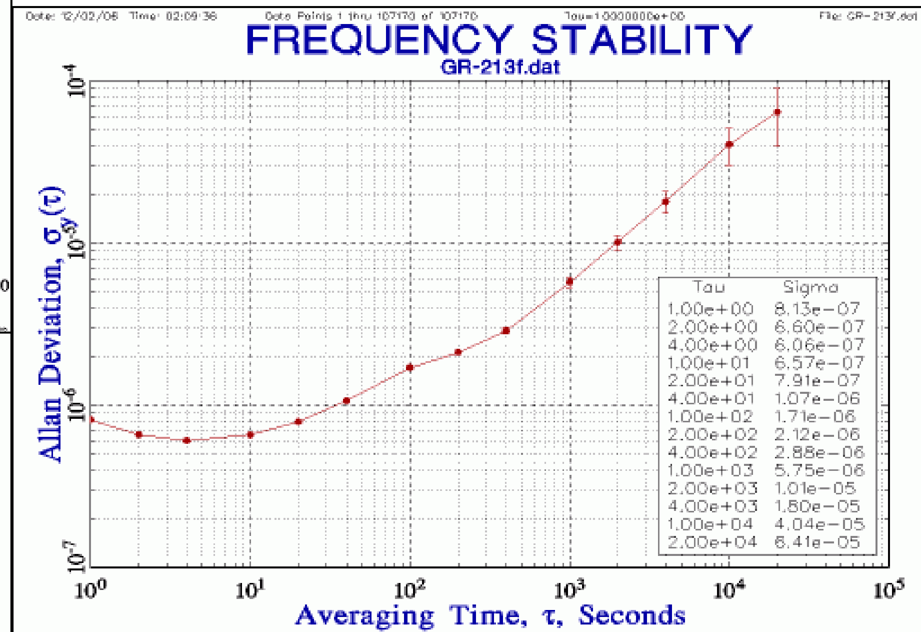
- 0.01, 1%
- General Radio Type 213 Audio Oscillator
- 1 ‘kc’; f = ~992.8 Hz
- ±1.3 mHz (60 x 1 s)
- Accuracy < 1%
- Count those 9’s
- ADEV is 10^{-6}…10^{-4}



10^{-2} tuning fork oscillator

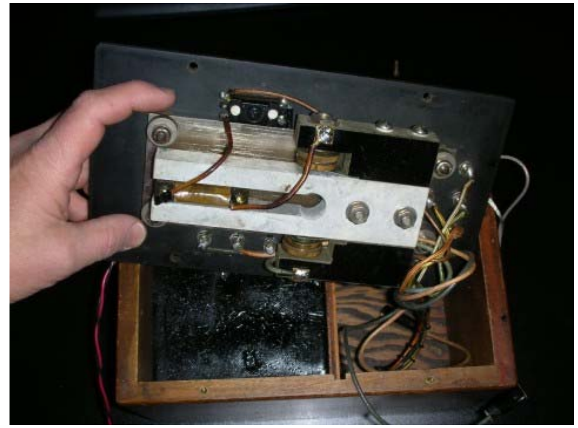


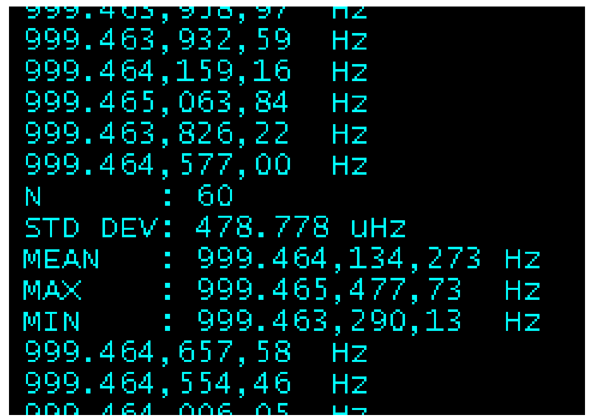




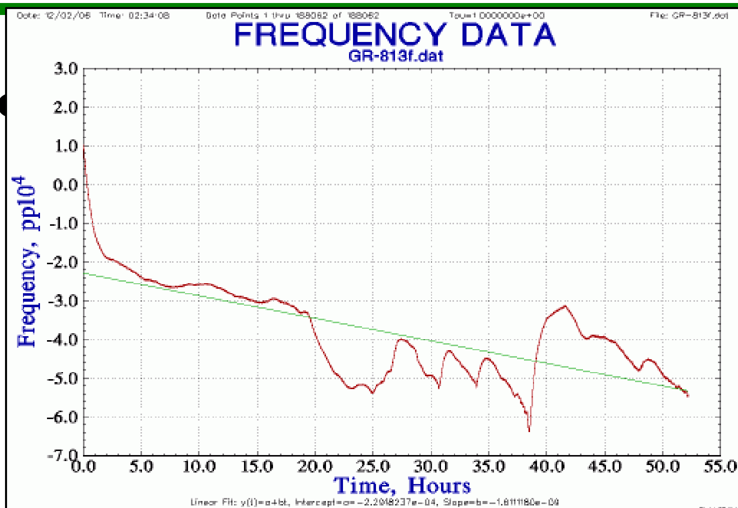
10^{-3} precision tuning fork

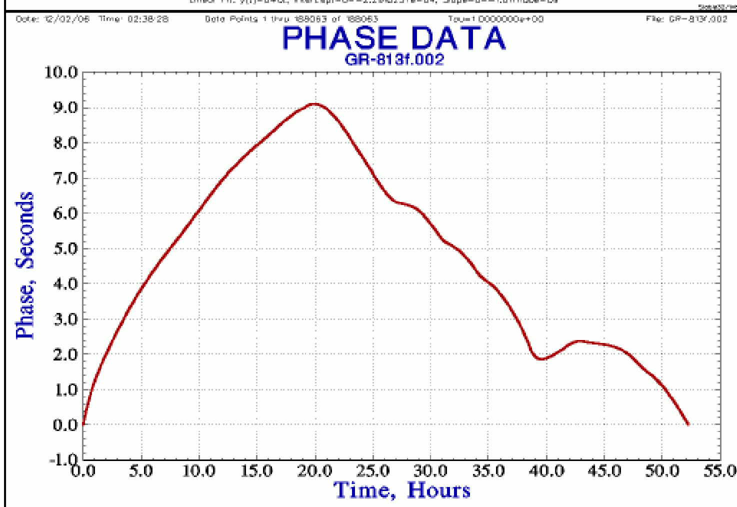
- 0.001, 0.1%, 1 ms/s
- General Radio Type 813
- 1 ‘kc’ tuning fork
- f = ~999.4 Hz
- ±400 µHz (60 x 1 s)
- Accuracy < 0.1%
- ADEV is $10^{-7} \ldots 10^{-4}$

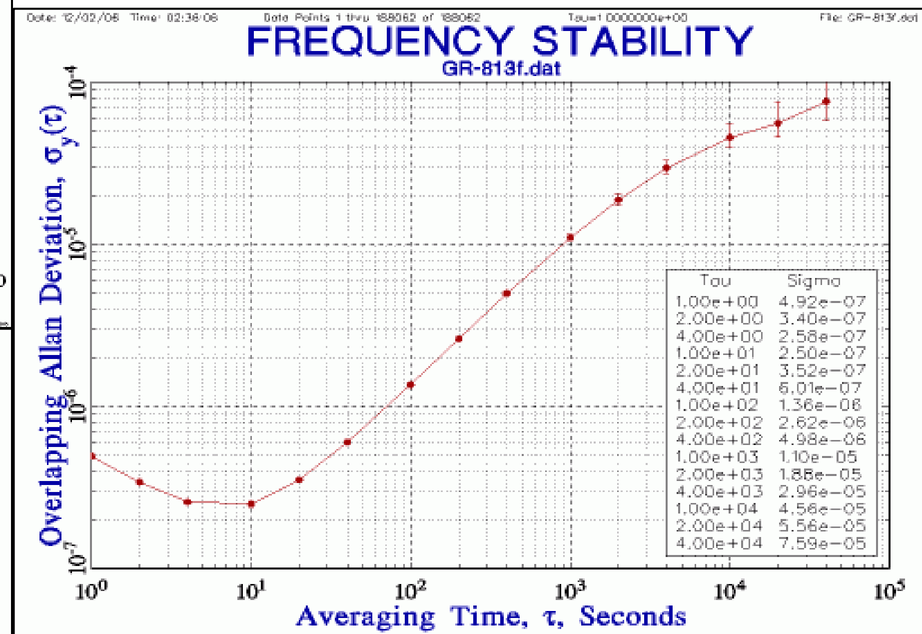




10^{-3} precision tuning fork

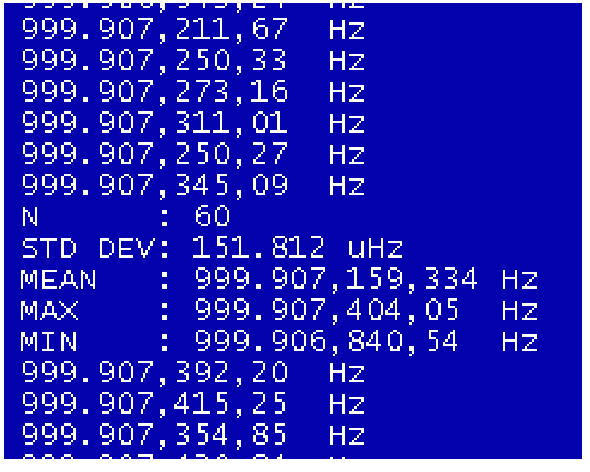


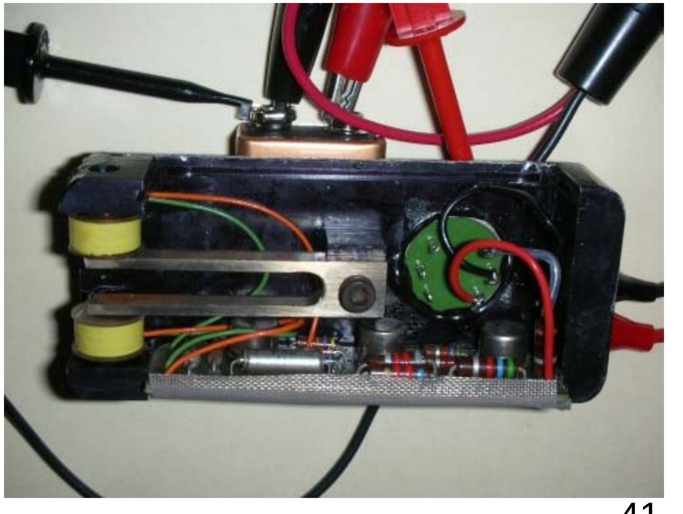




10^{-4} mechanical oscillator

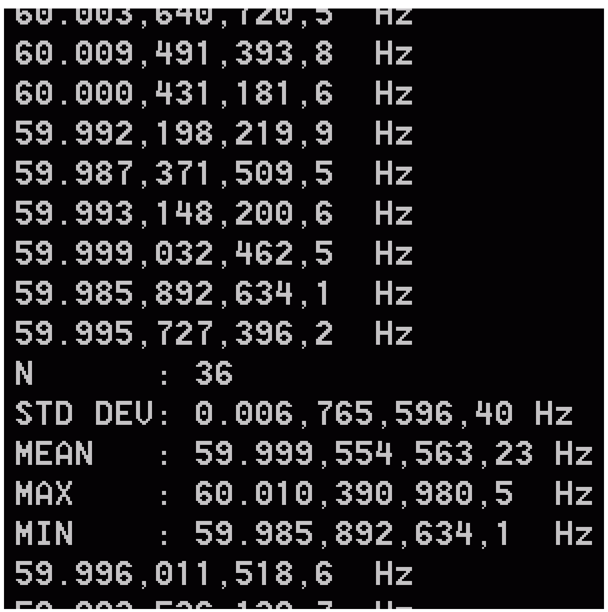
- 0.01%, 100 ppm
- Mechanical oscillator
- “Four 9’s”


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

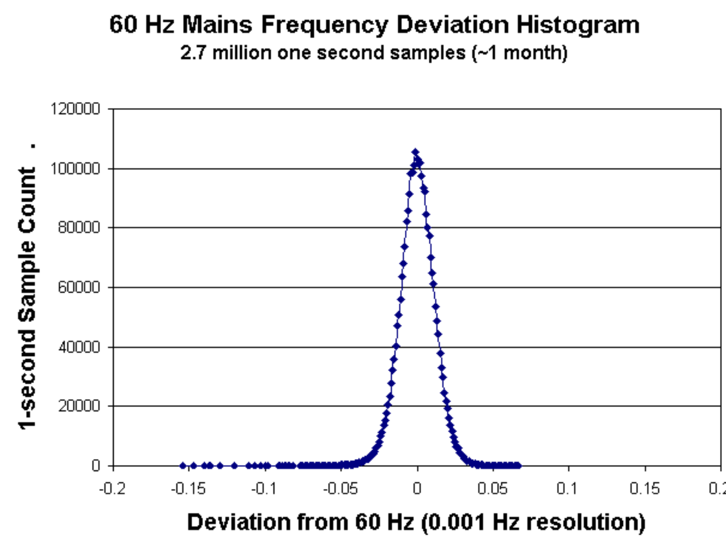


10^{-5} mains (line frequency)

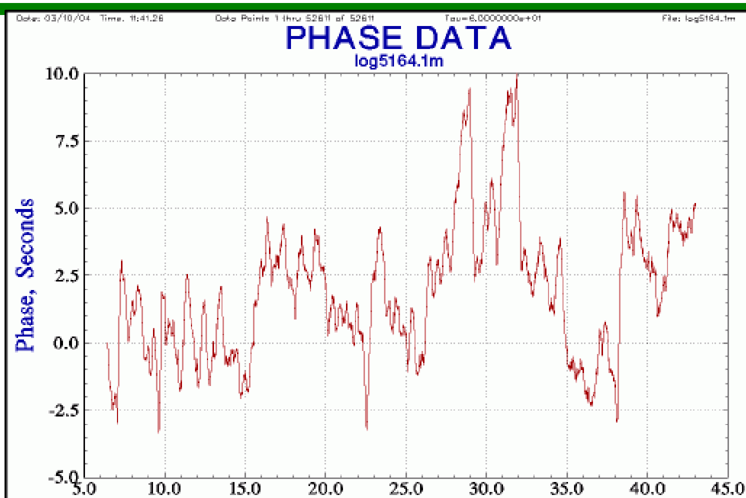
- 0.001%, 10 ppm
- 60± Hz

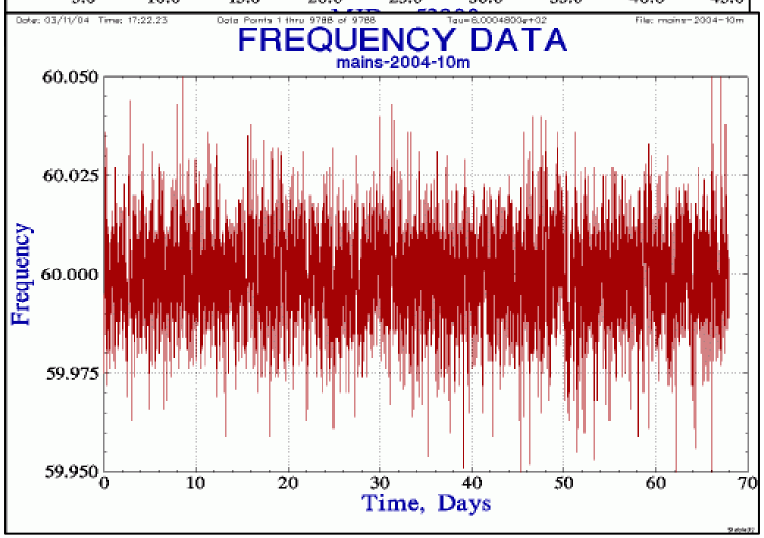


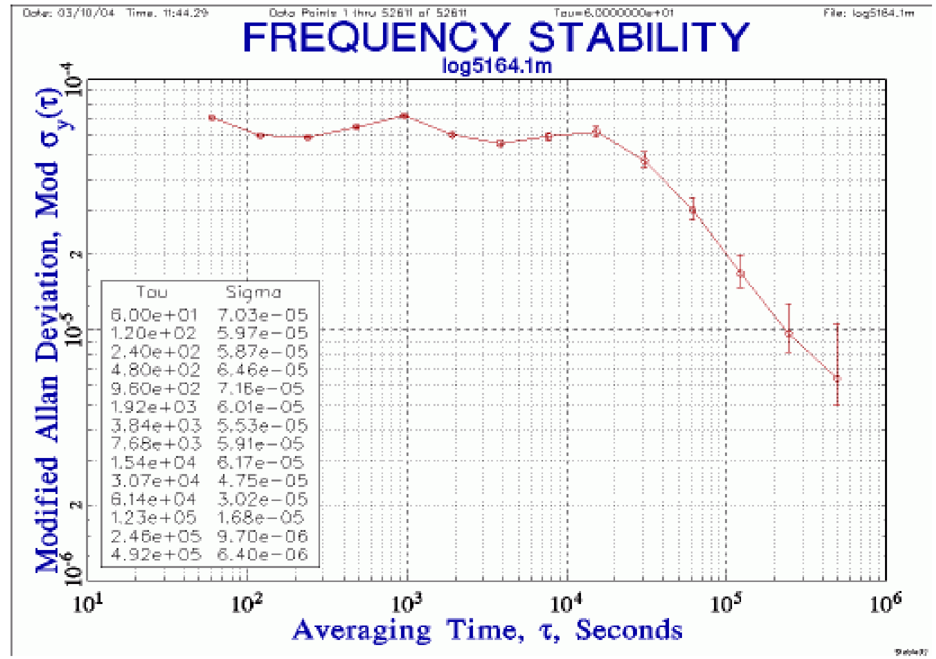
```
60.009,491,393,8  Hz
60.000,431,181,6  Hz
59.992,198,219,9  Hz
59.987,371,509,5  Hz
59.993,148,200,6  Hz
59.999,032,462,5  Hz
59.985,892,634,1  Hz
59.995,727,396,2  Hz
N       : 36
STD DEV: 0.006,765,596,40 Hz
MEAN    : 59.999,554,563,23 Hz
MAX     : 60.010,390,980,5  Hz
MIN     : 59.985,892,634,1  Hz
59.996,011,518,6  Hz
```



10^{-5} mains (line frequency)

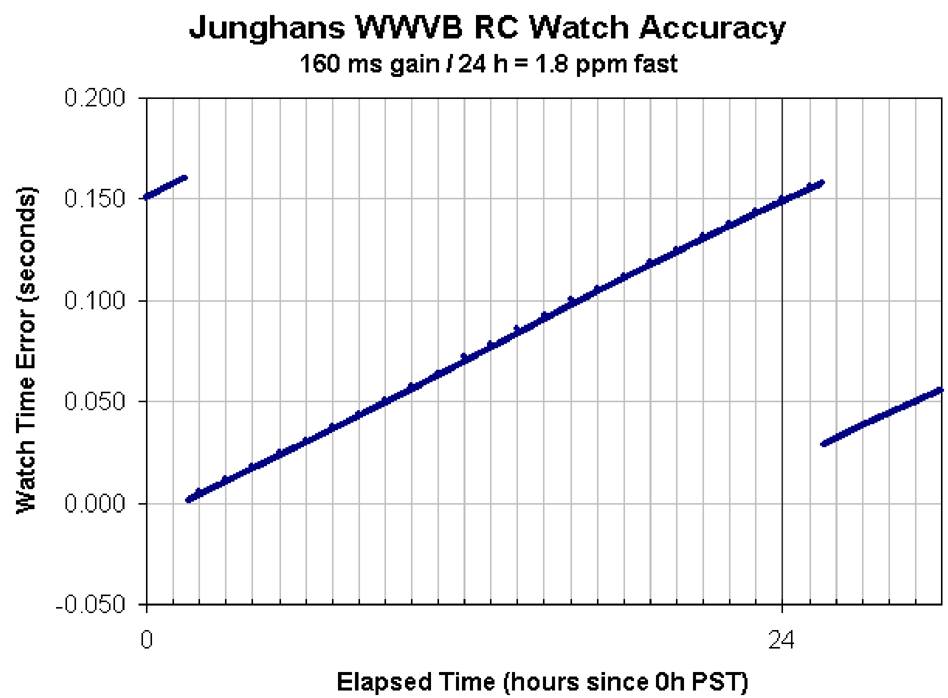






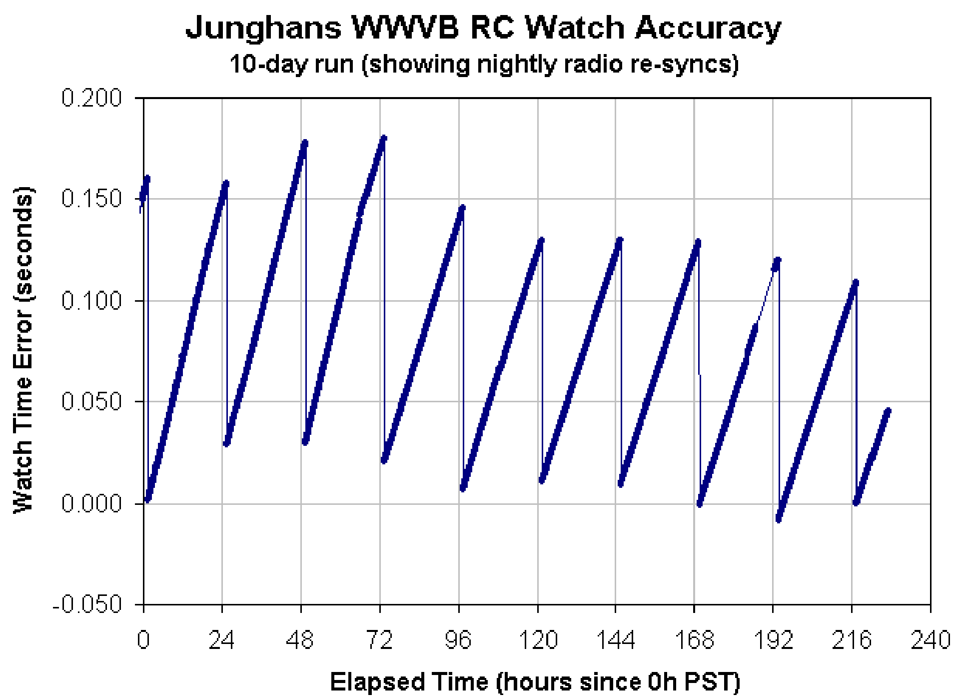
10^{-6} quartz watch (RC)

- 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

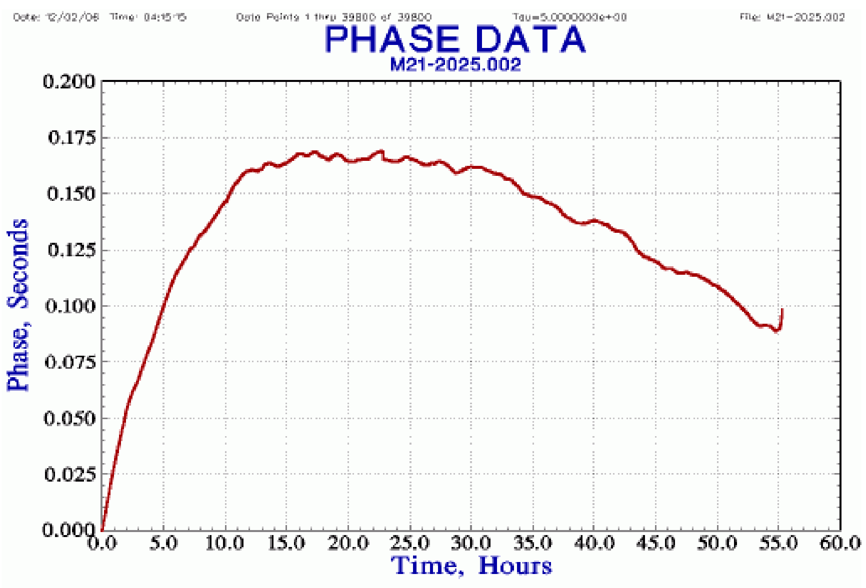


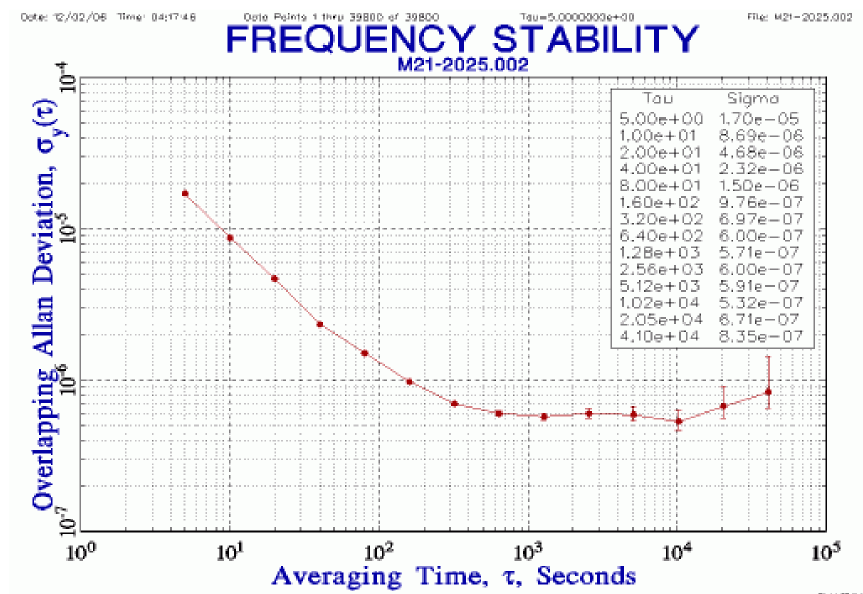
10^{-7} chronometer

- 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	2½	+ ½		
5	+0	2½	0	¼	
6	+0	3	+ ½	¼	
7	+0	3	0	¼	
8	+0	3½	+ ½	¼	
9	–	–	–	–	Not wound
10	+0	4	+ ¼	–	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

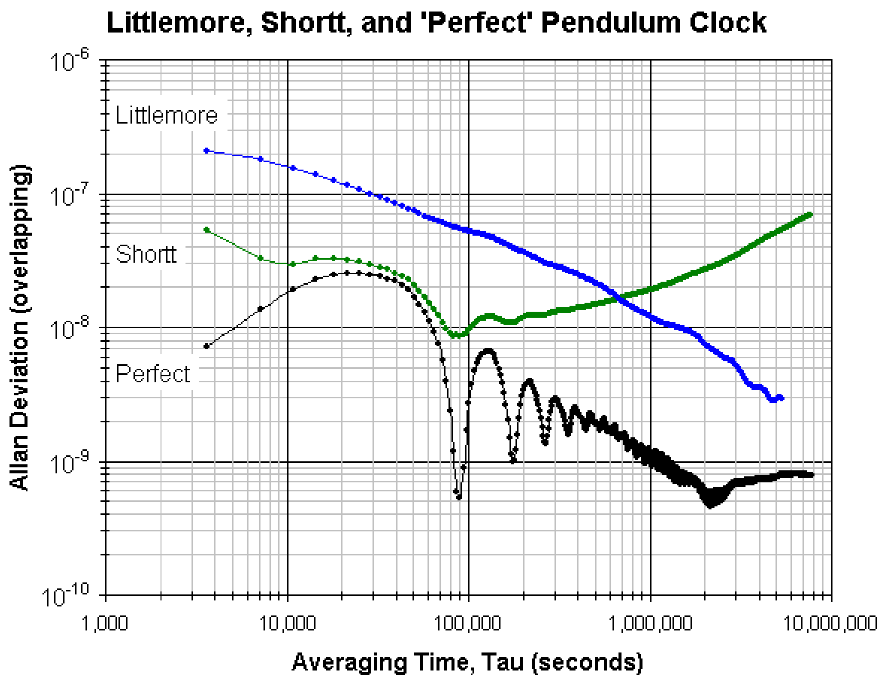
10^{-8} pendulum clock

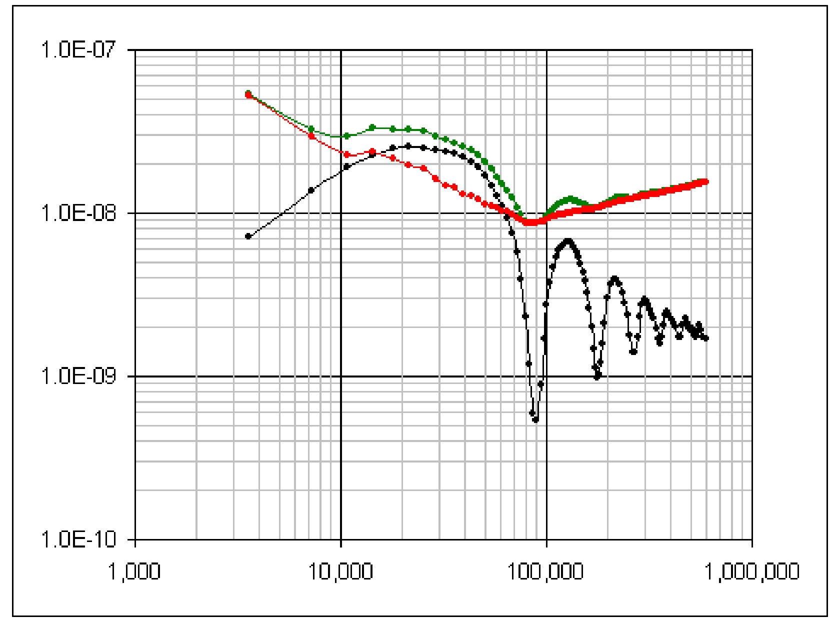
- 0.01 ppm, 10 ppb
  10 ns/s, 864 µs/d
- Shortt,
  Fedchenko,
  Riefler,
  'Littlemore'

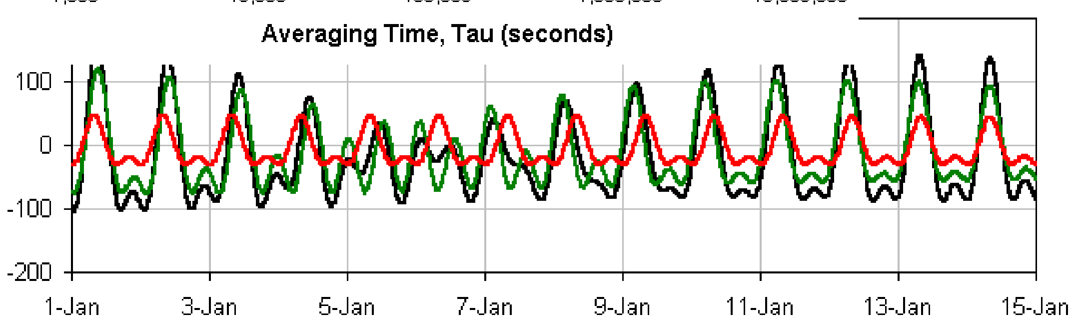
10^{-8} pendulum clock

- Amazing astronomical pendulum clocks
- Several centuries of understanding and perfection. Limitations addressed:
  - temperature, humidity, mass, friction, metallurgy, escapement, master/slave, vacuum, isochronous suspension, etc.
- When all factors solved, the best pendulum clock is just a good gravimeter

10^{-8} pendulum clock



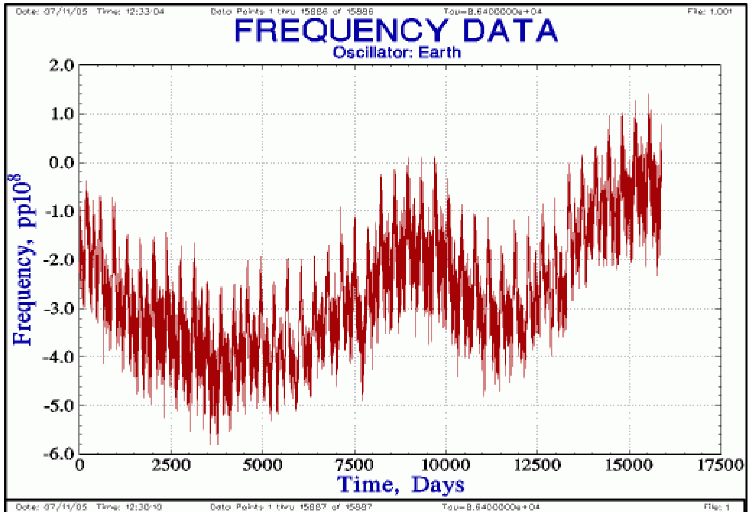


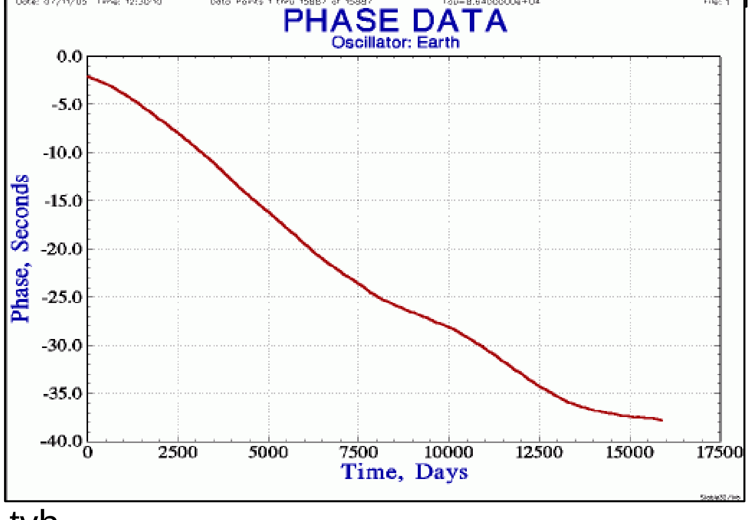


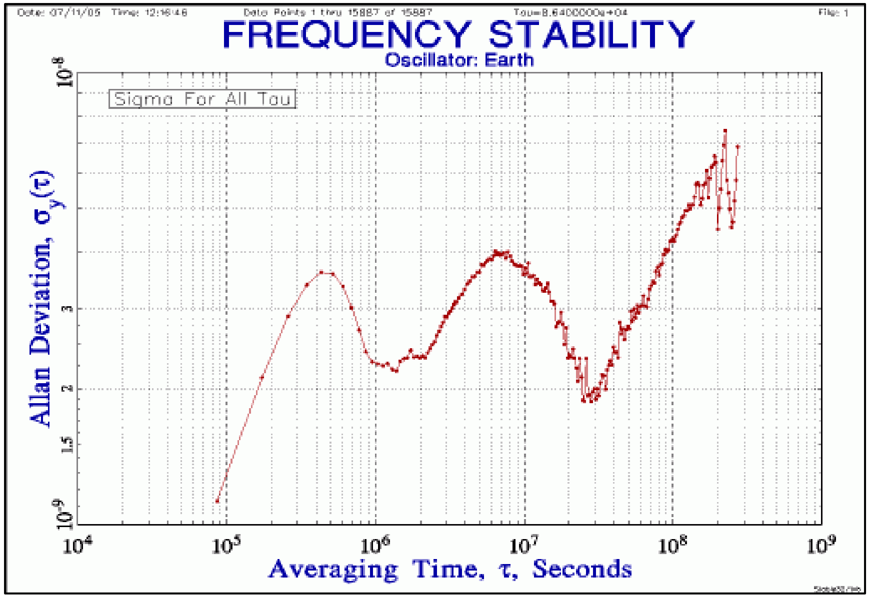
10^{-9} earth

- 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

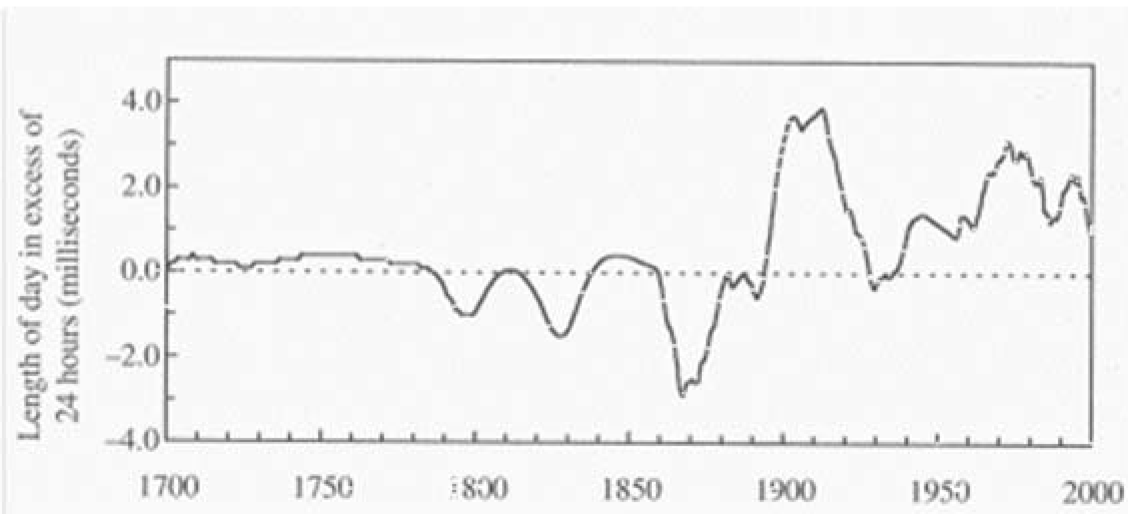

FREQUENCY DATA
Oscillator: Earth
Frequency, pp10^8
Time, Days


PHASE DATA
Oscillator: Earth
Phase, Seconds
Time, Days


FREQUENCY STABILITY
Oscillator: Earth
Sigma For All Tau
Allan Deviation, σy(τ)
Averaging Time, τ, Seconds

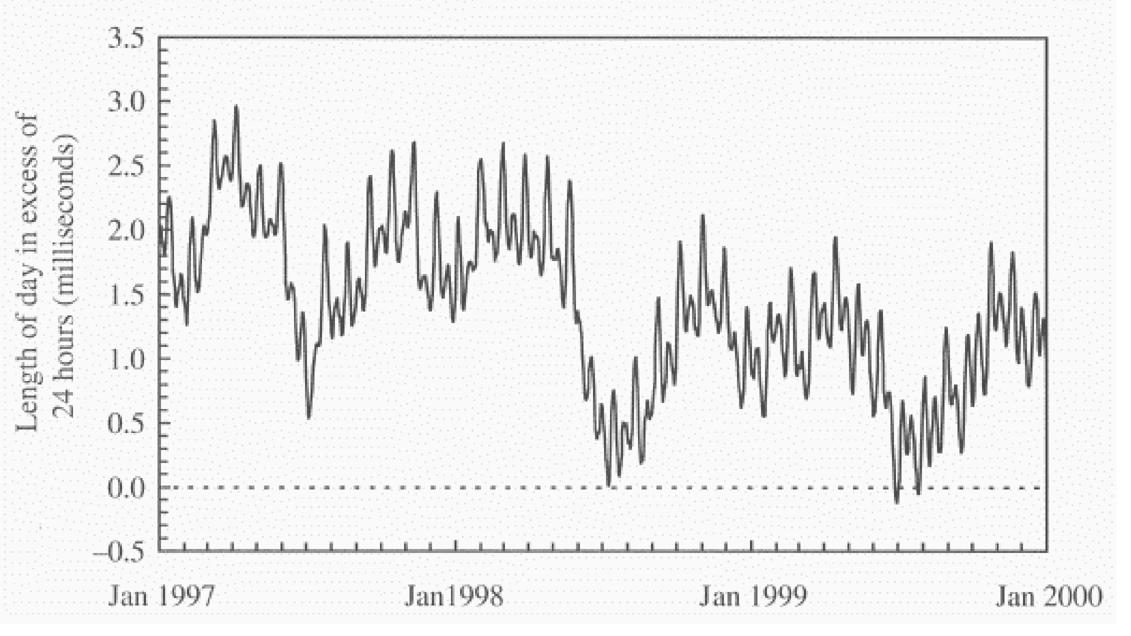
10^{-9} earth clock

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

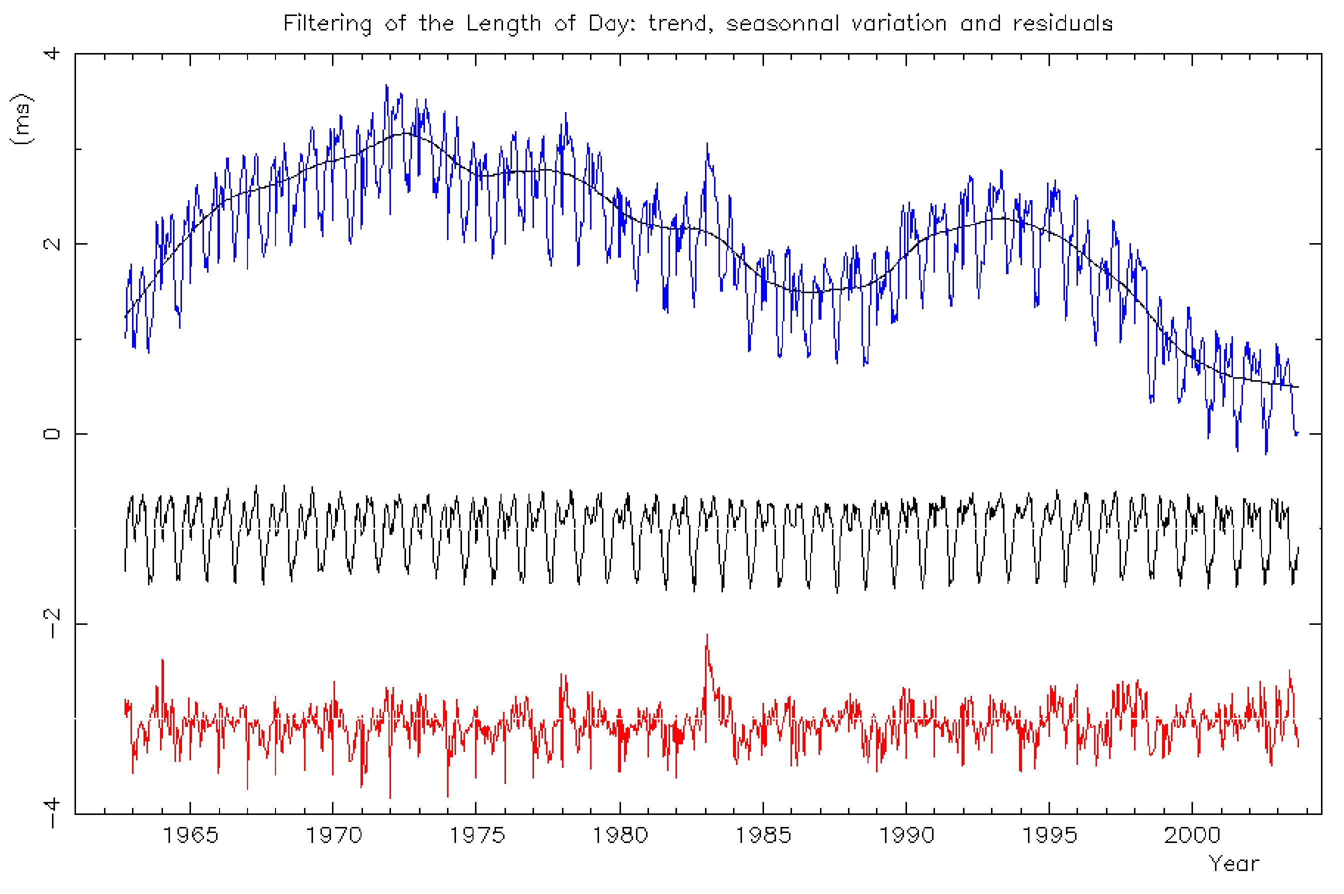


10^{-9} earth clock

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



10^{-9} earth clock

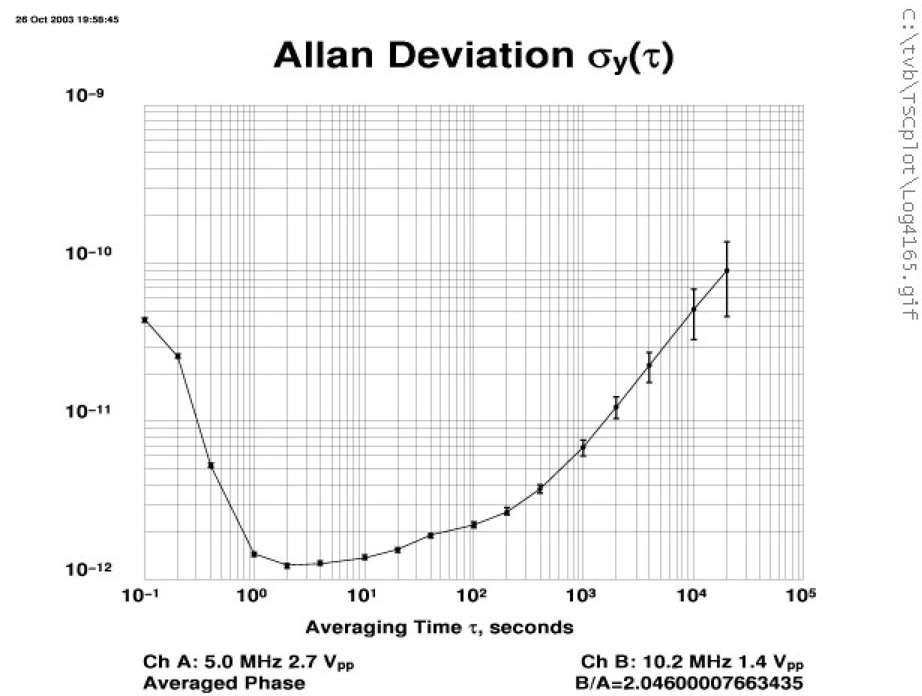


10^{-9} earth frequency standard

- 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)

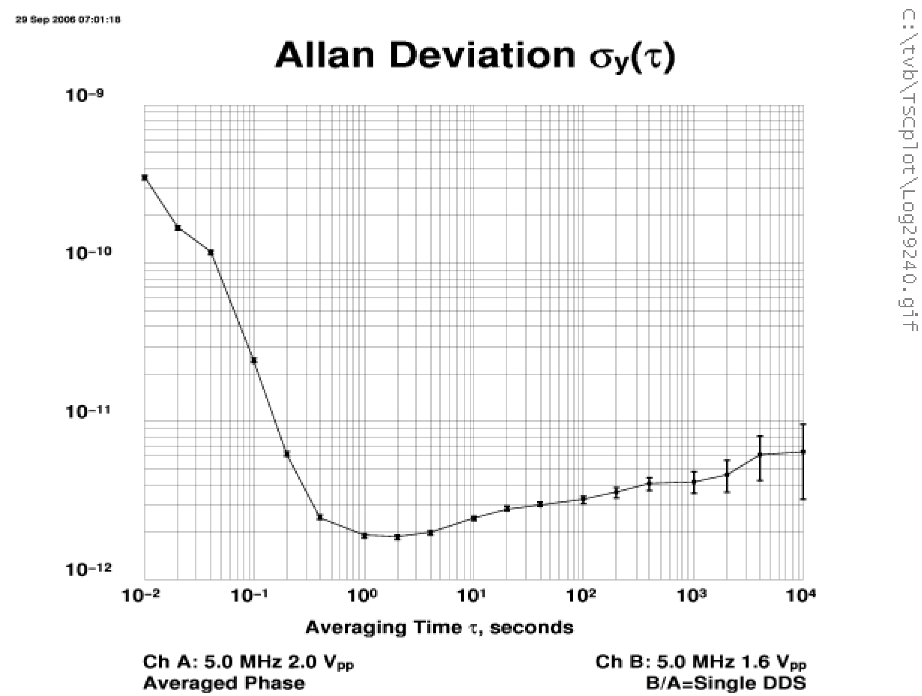
10^{-10} ocxo

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



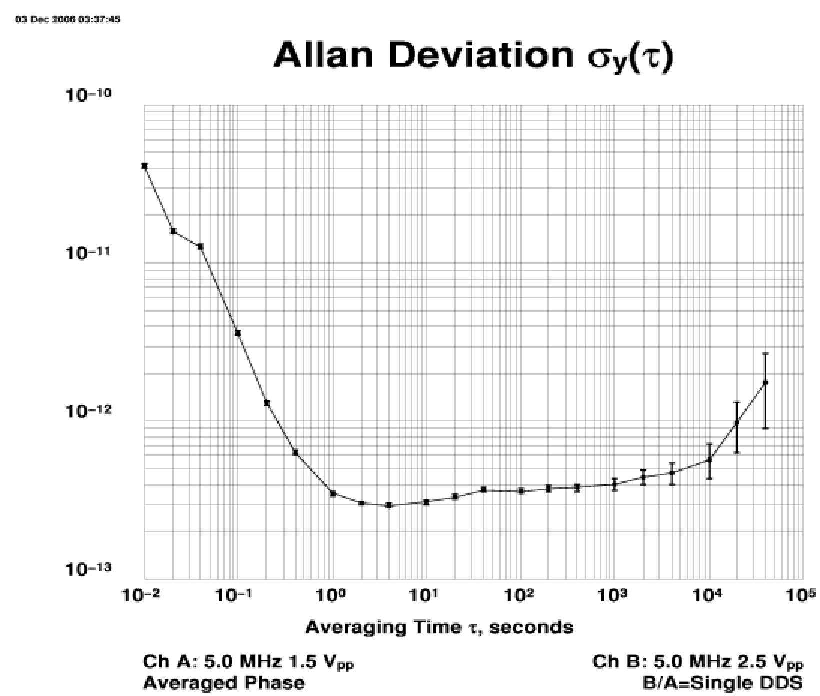
10^{-11} good ocxo

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



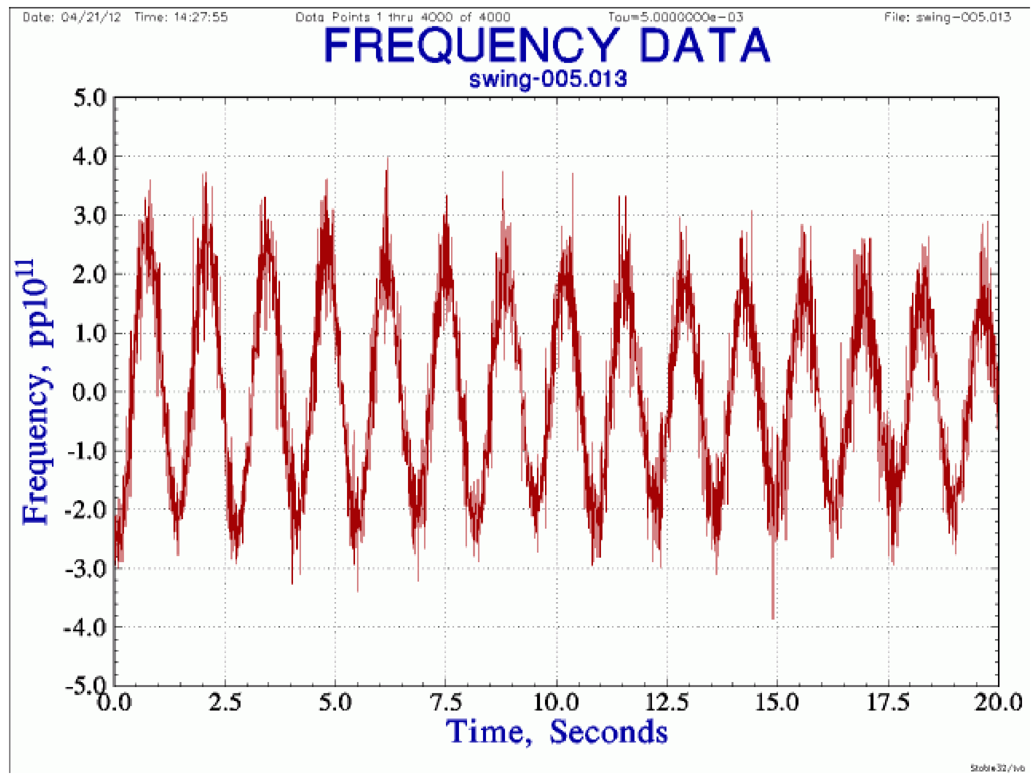
10^{-12} excellent ocxo

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



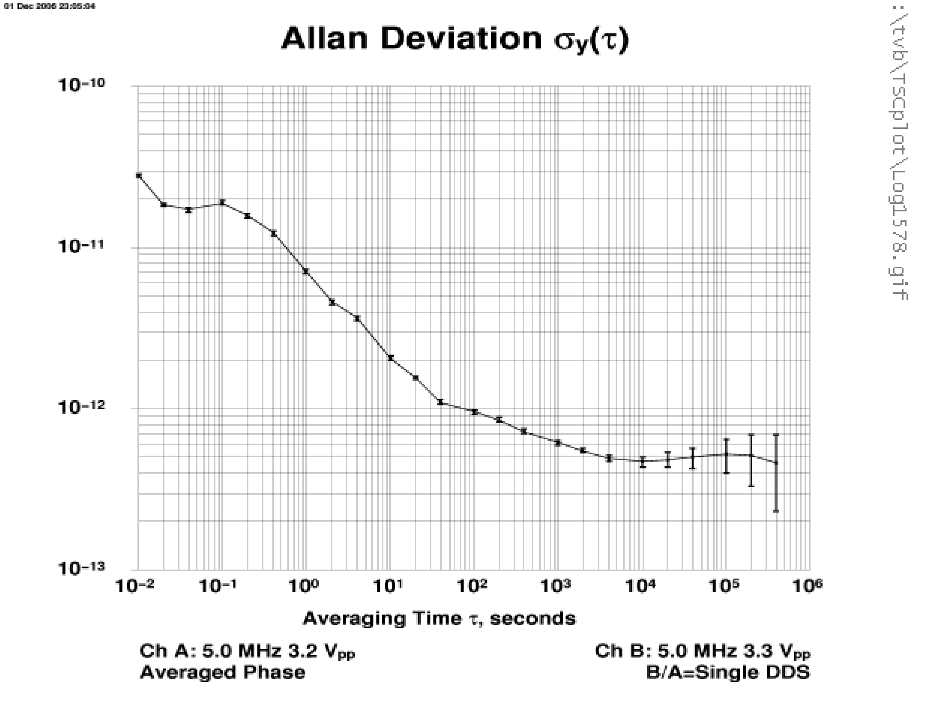
10^{-12} excellent ocxo

- Oscillator on a string, swinging
- Acceleration sensitivity
- Tilt
- Turnover
- ±9.8 m/s^2



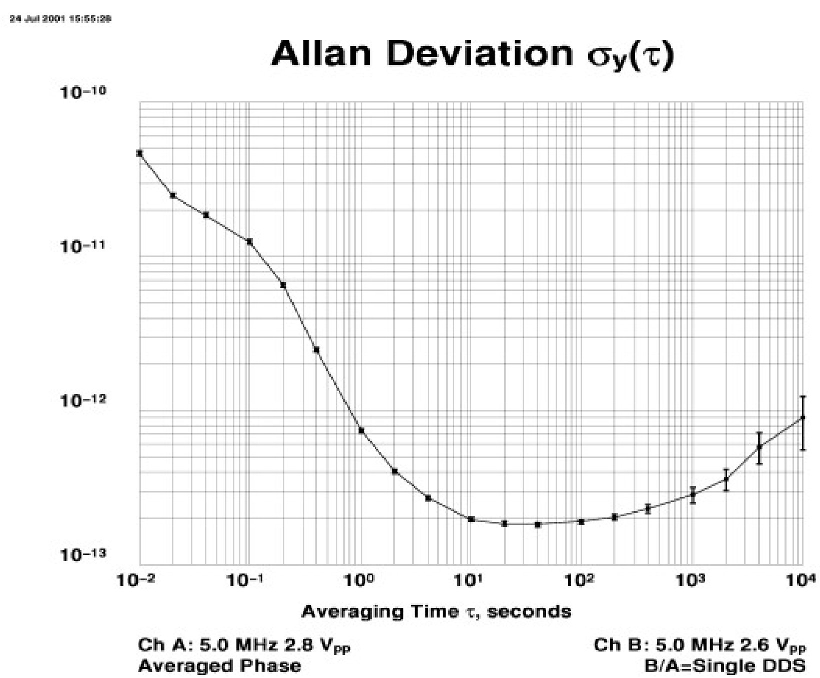
10^{-13} rubidium

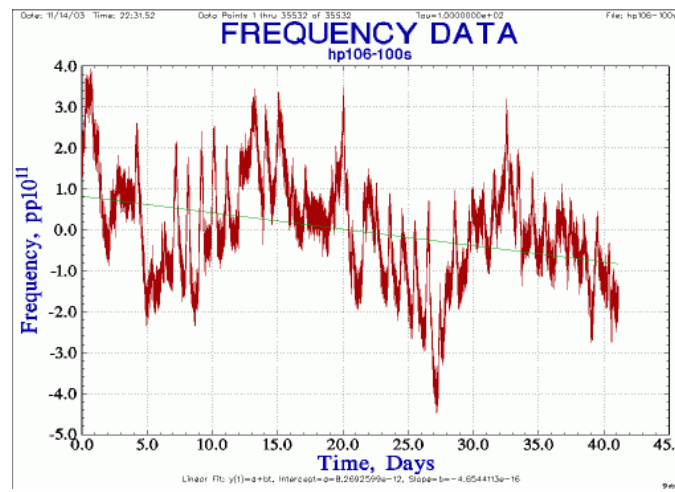
- 8.64 ns/d (~10 ns/d)
- $\sim 10^{-13}$ mid-term
- $\sim 1 \times 10^{-11}$/m drift



10^{-13} hp 106B quartz

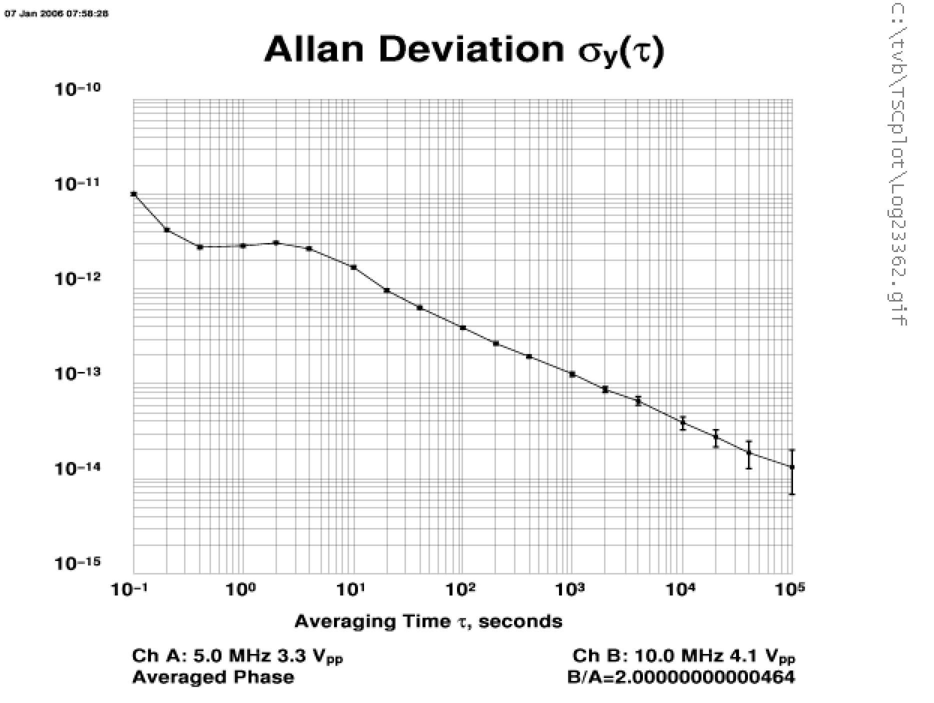
- Best hp quartz
- ~4×10^{-13}/d drift





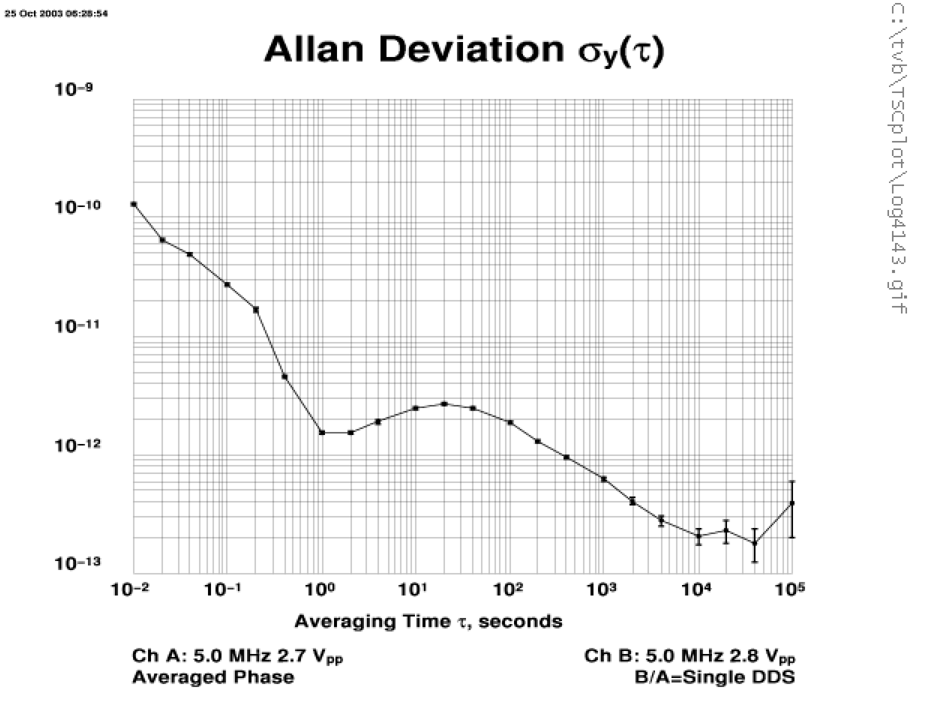
10^{-14} cesium

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



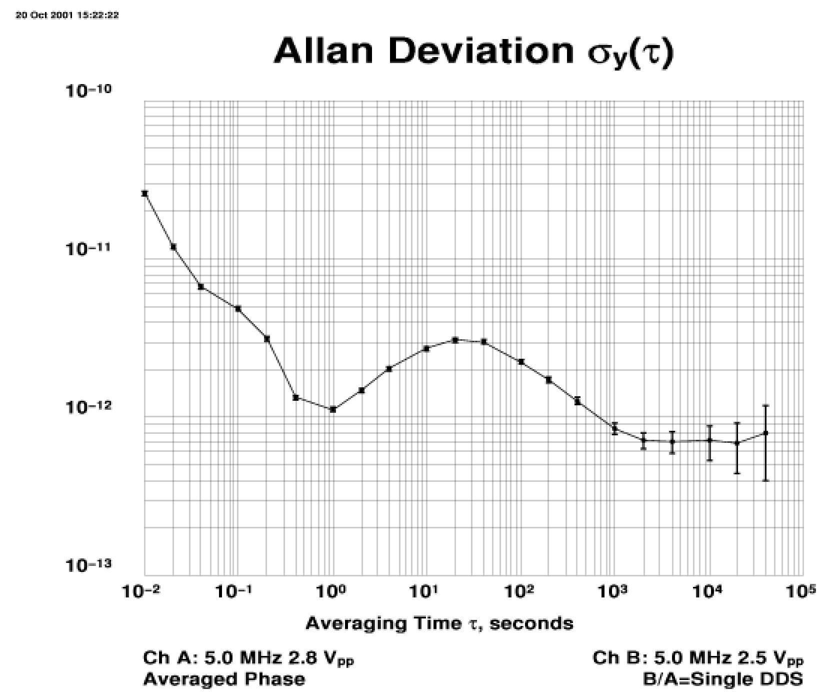
10^{-14} more cesium

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



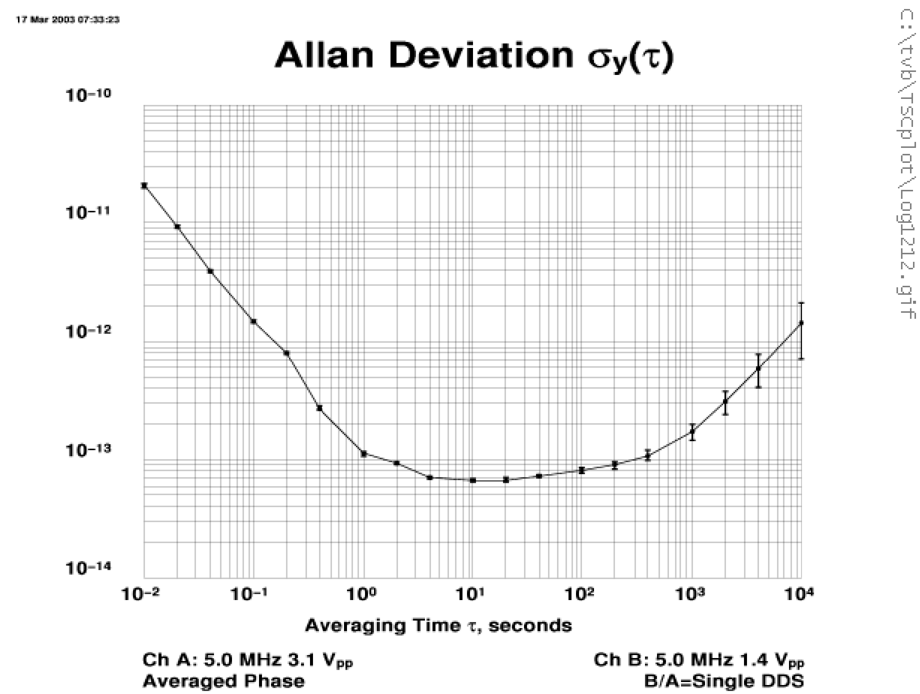
10^{-14} another cesium

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



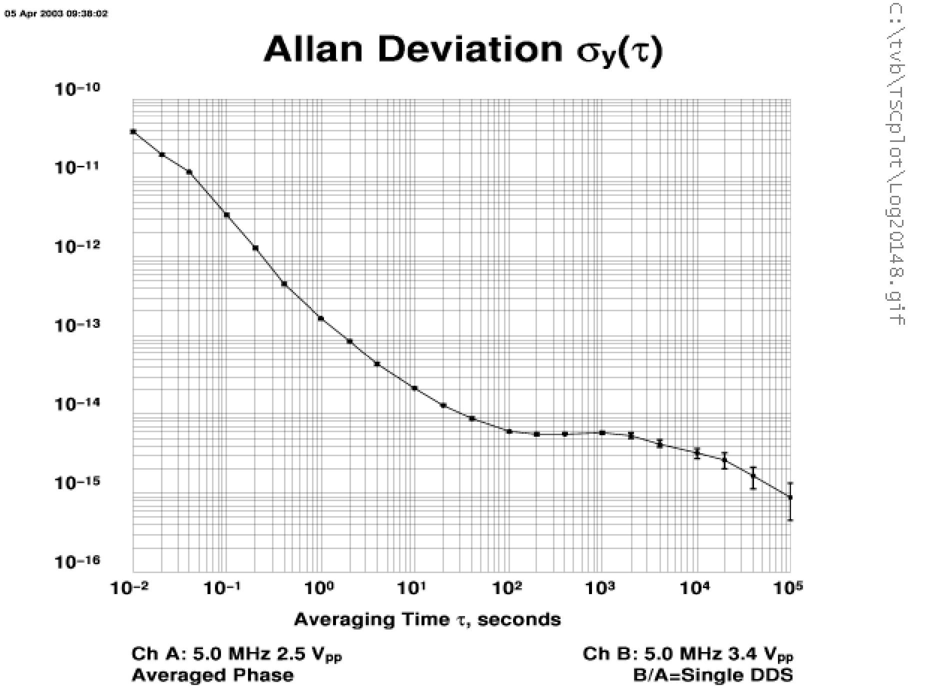
10^{-14} BVA quartz

- 10^{-13}…10^{-14} short-term
- 10^{-11}…10^{-12} /d drift
- Best quartz



10^{-15} active h-maser

- 86.4 ps/d
- Near 1×10^{-15} @1d
- Most stable

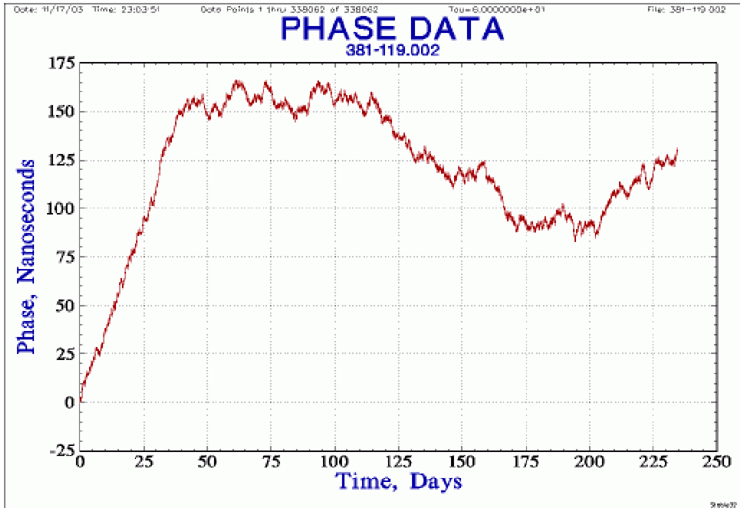


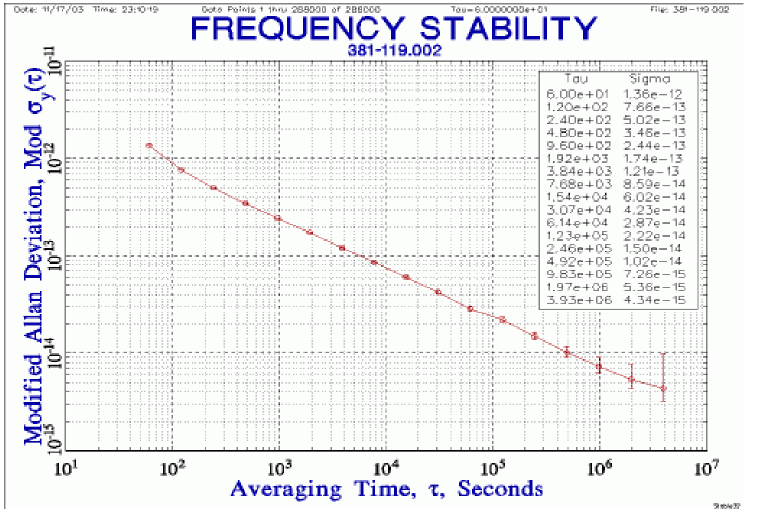
10^{-15} active h-maser

- M.A.S.E.R. = **M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation
- As in LASER (**L**ight)…
- ***M**eans of **A**cquiring **S**upport for **E**xpensive **R**esearch*

10^{-15} cesium, long-term

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





Powers of ten – summary

- 10% to 10^{-15} – 15 orders of magnitude

Outline

- 0 Introduction to T&F
- 1 The best clock
- 2 Powers of ten
- 3 GREAT adventure

Relativity, clocks, and time

- Einstein said gravity affects ***time*** itself!
- Theory of relativity; clocks; time dilation
- S.R. – *high speed* slows time down
  - moving clocks run slower than…
- G.R. – *strong gravity* slows time down
  - lower clocks run slower than…
  - higher clocks run faster than…
- Can this be tested with atomic clocks?

Relativity at home

- Cannot take clocks at high enough speed
  - no rockets or planes at home
- But *can* take clocks to high elevation
  - we have mountains
  - Mt Rainier road
  - Paradise Inn

The great idea

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

Project GRE^{2}AT

- **G**eneral **R**elativity **E**instein/**E**ssen **A**nniversary **T**est (2005)
  - 100th anniversary (Einstein) theory of relativity
  - 50th anniversary (Essen) first cesium clock
- Opportunity to:
  - put my atomic collection to interesting use
  - perform fun (unusual) activity for children
  - similar experiments first performed in 1970's

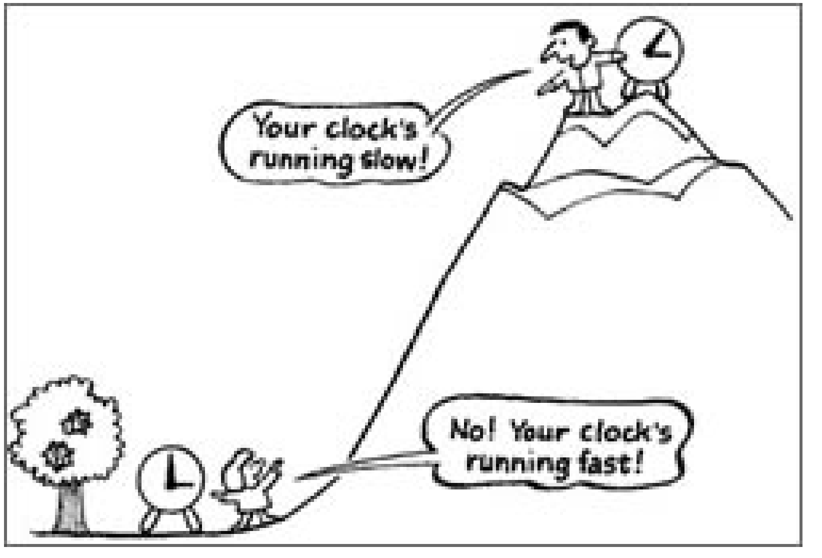
Math Detail

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

- 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 $\Delta T = \sum \Delta f \times T$

Back of envelope calculation

- According to GR, clock frequency changes according to height difference, h
  - $\approx gh/c^2$
- On earth, this is
  - $\approx 1.09\times10^{-16}$/meter
- Units: s/s/m
- Infinitesimal!



From NPL website

10^{-16} way is too small, but

- If you go up 1 km instead of 1 m, then
  $\Delta f = 1.1\times10^{-13} = 0.11$ ps/s
- And stay up there 24 hours, then
  $\Delta T = \Delta f \times 86400 \text{ s} = 9.5$ ns
- 9 ns is “huge”; so this looks possible!
- Gravitational time dilation rule-of-thumb

  10 ns / day / km

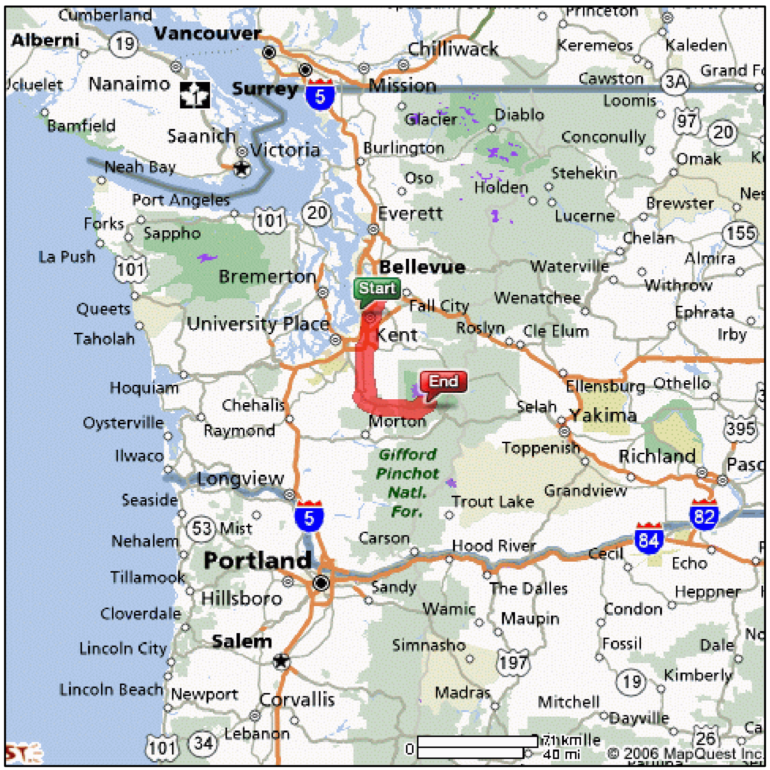
Key parameters

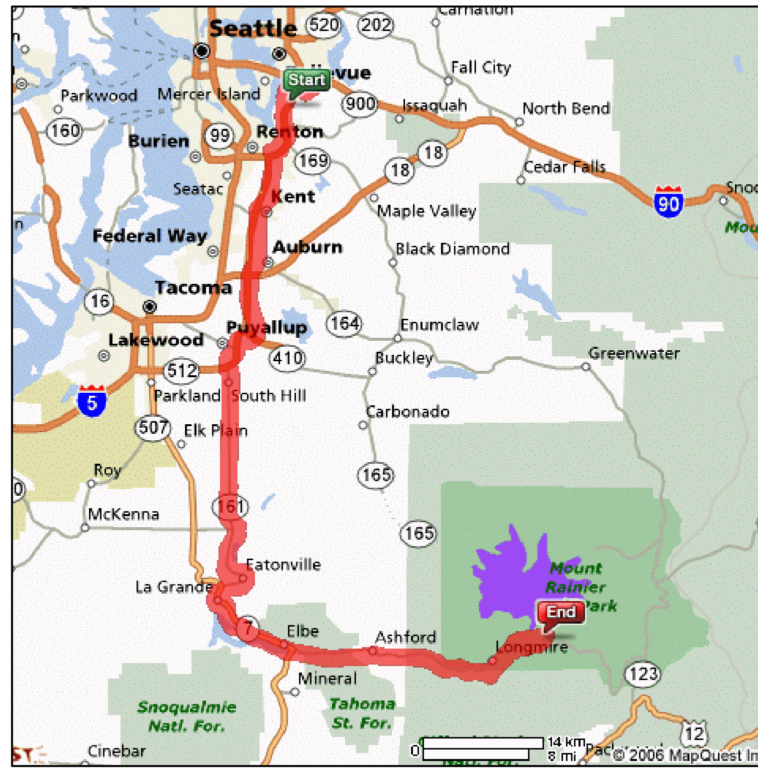
- Location
  - how high
  - how long
- Clocks
  - how stable
  - how many
- Counters
  - how precise

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

Bellevue to Mt Rainier

- Just 100 miles away (~2½ hours)



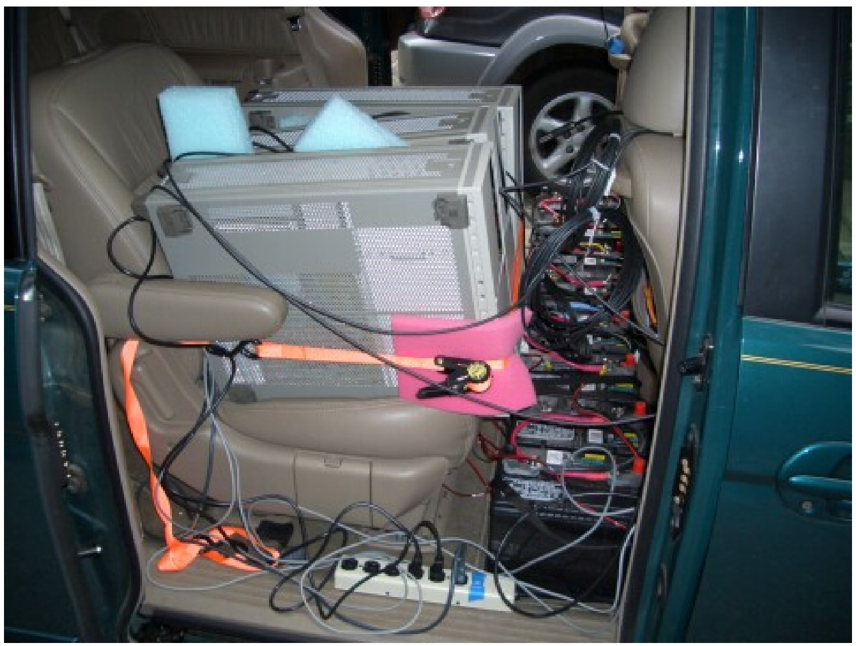


The GREAT trip, day 1

- 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 in 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, day 3

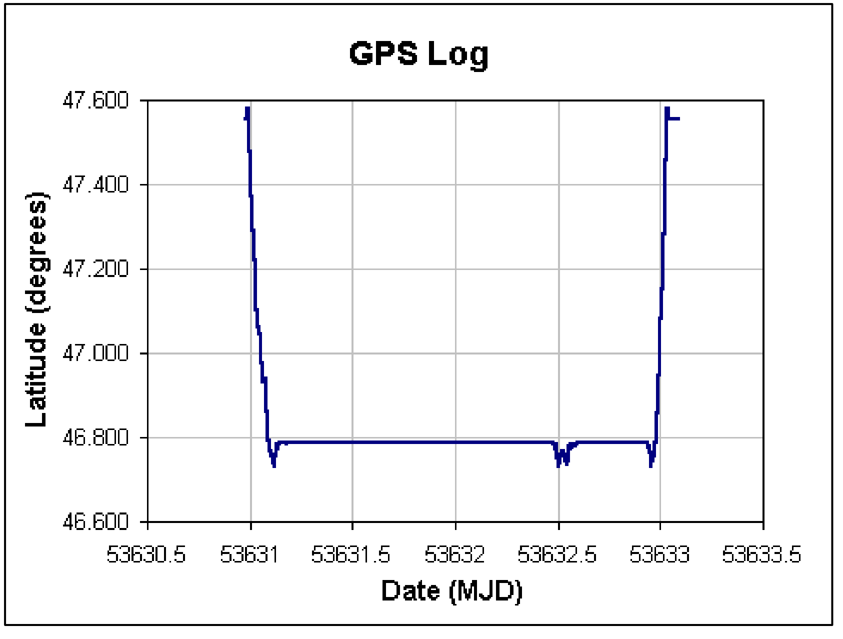
- Carry clocks & TIC back inside, reconnect same cables, *resume* phase comparison.

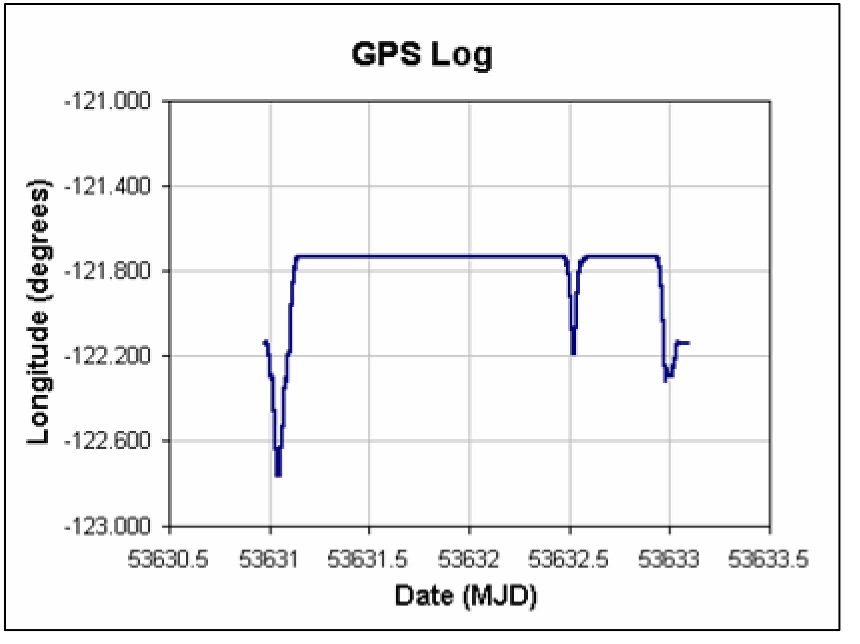
Two questions

- Results unknowable until 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 RS232 log

Plots from GPS Log

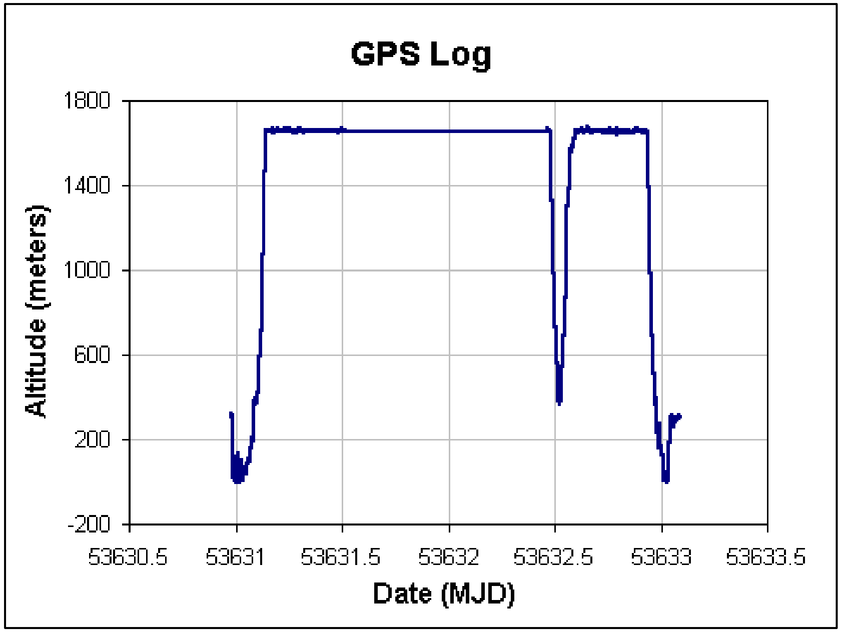
- Latitude, Longitude

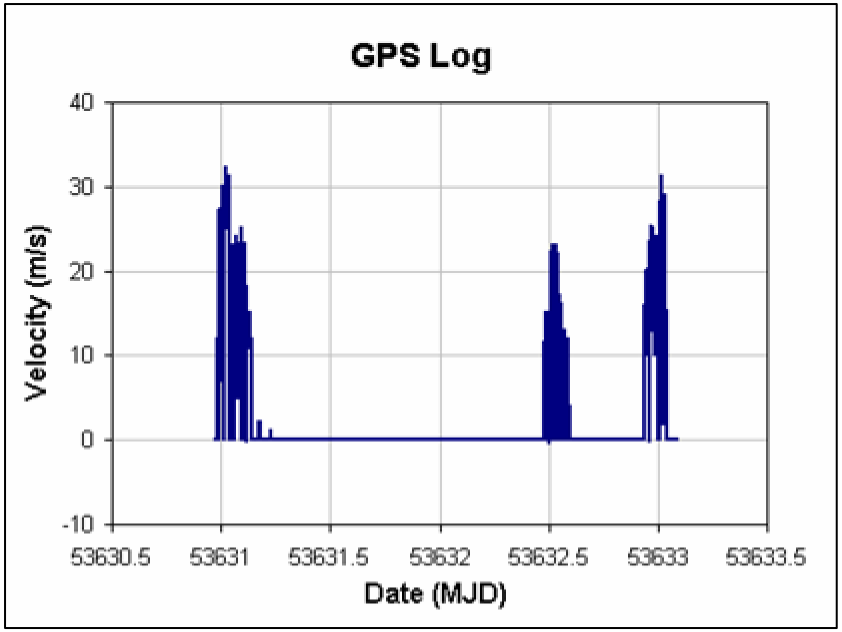




Plots from GPS Log

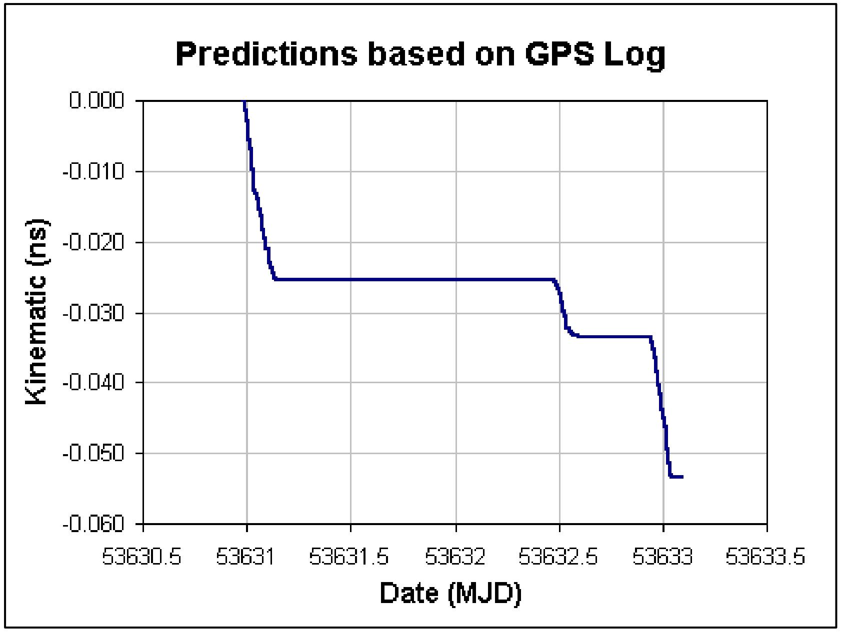
- Altitude, Velocity

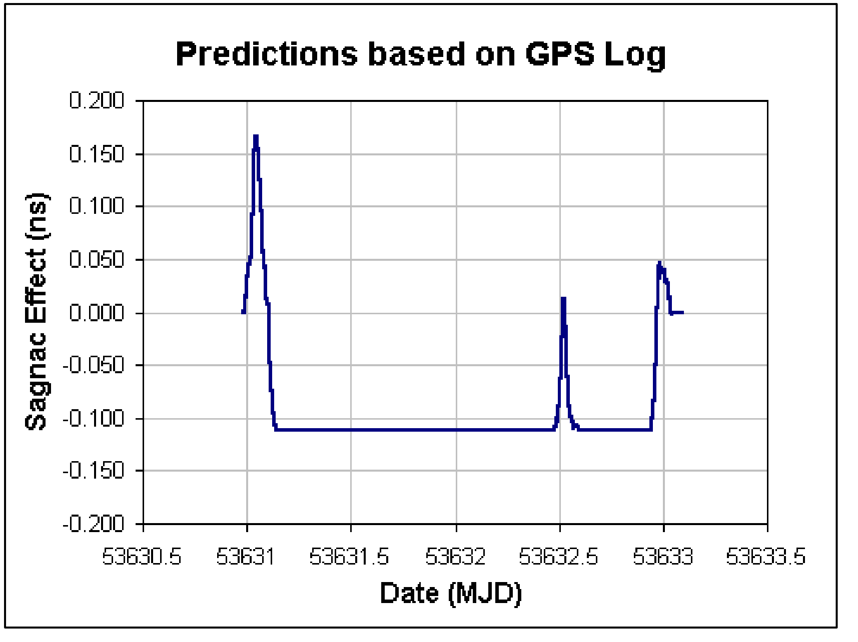




Predictions from GPS Log

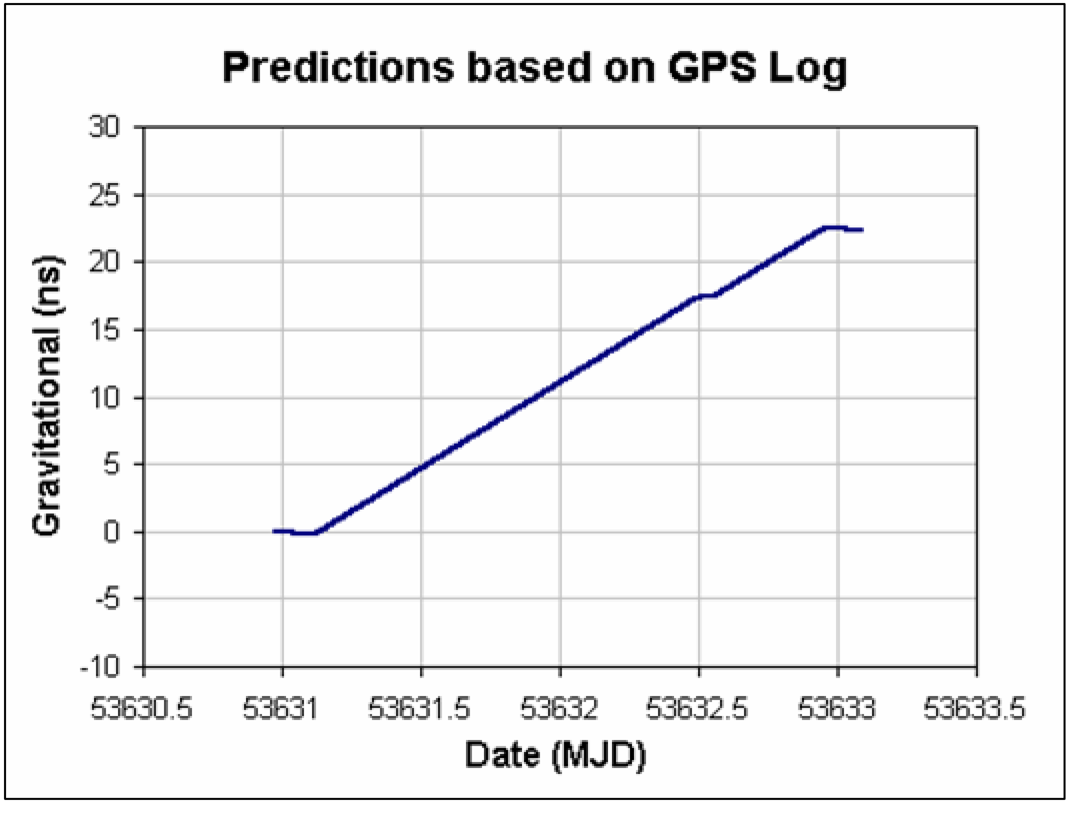
- SR (velocity): 50 ps
- Sagnac effect: ±150 ps (net 1 ps)



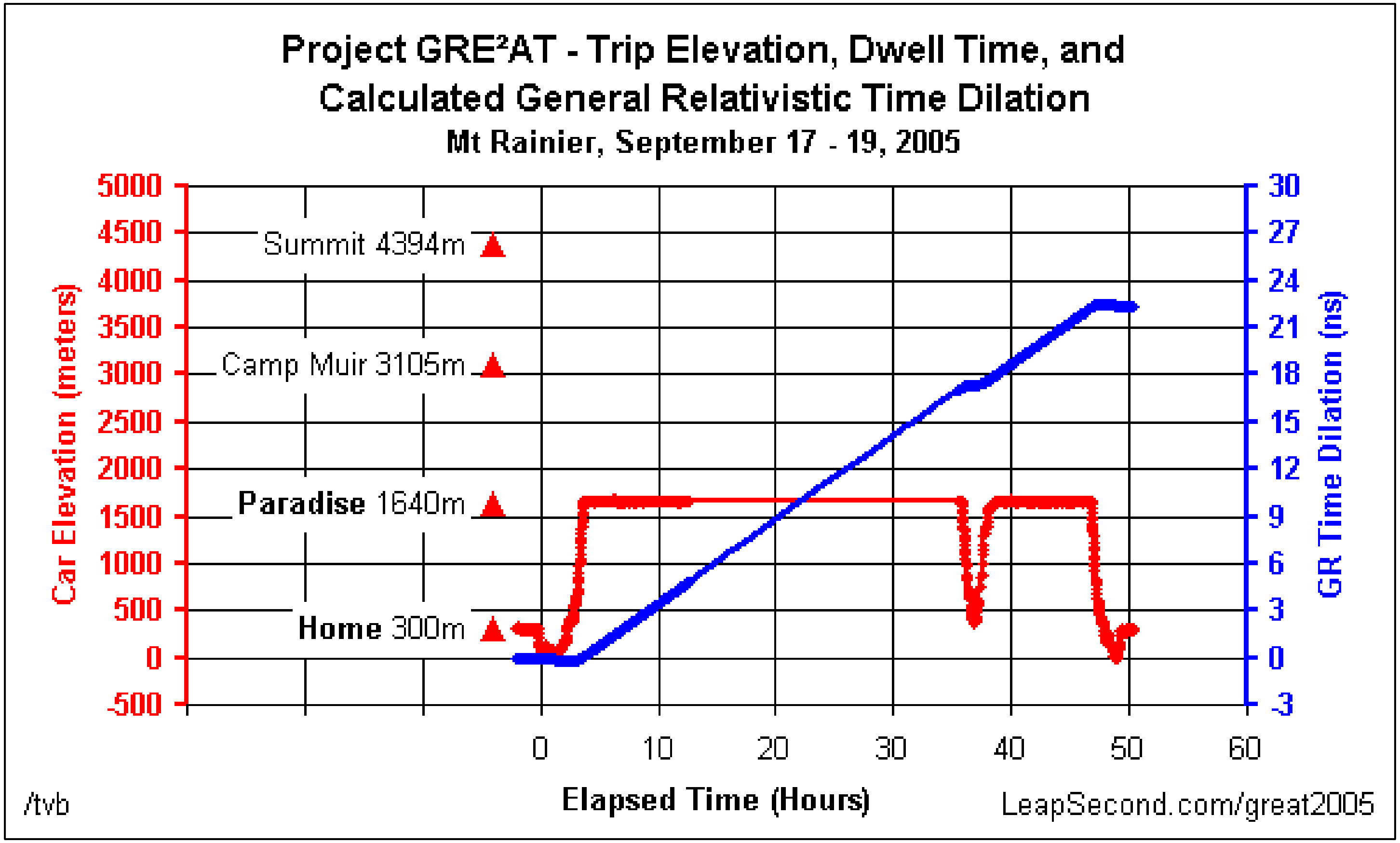


Predictions from GPS Log

- GR (gravitational): **22.37 ns**

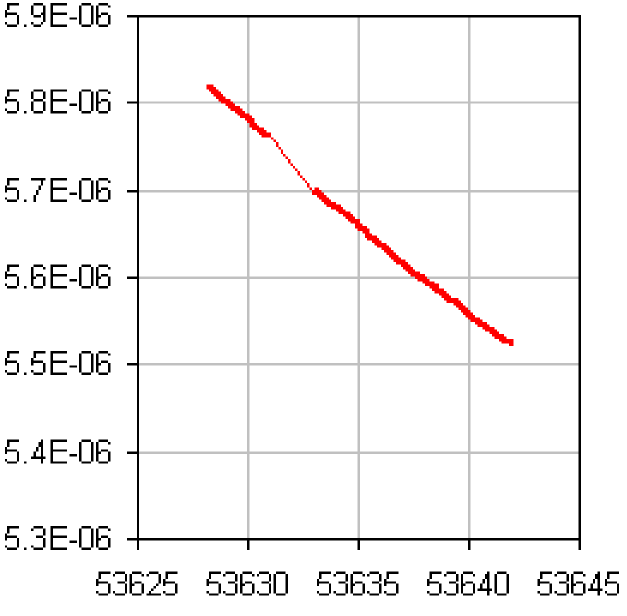


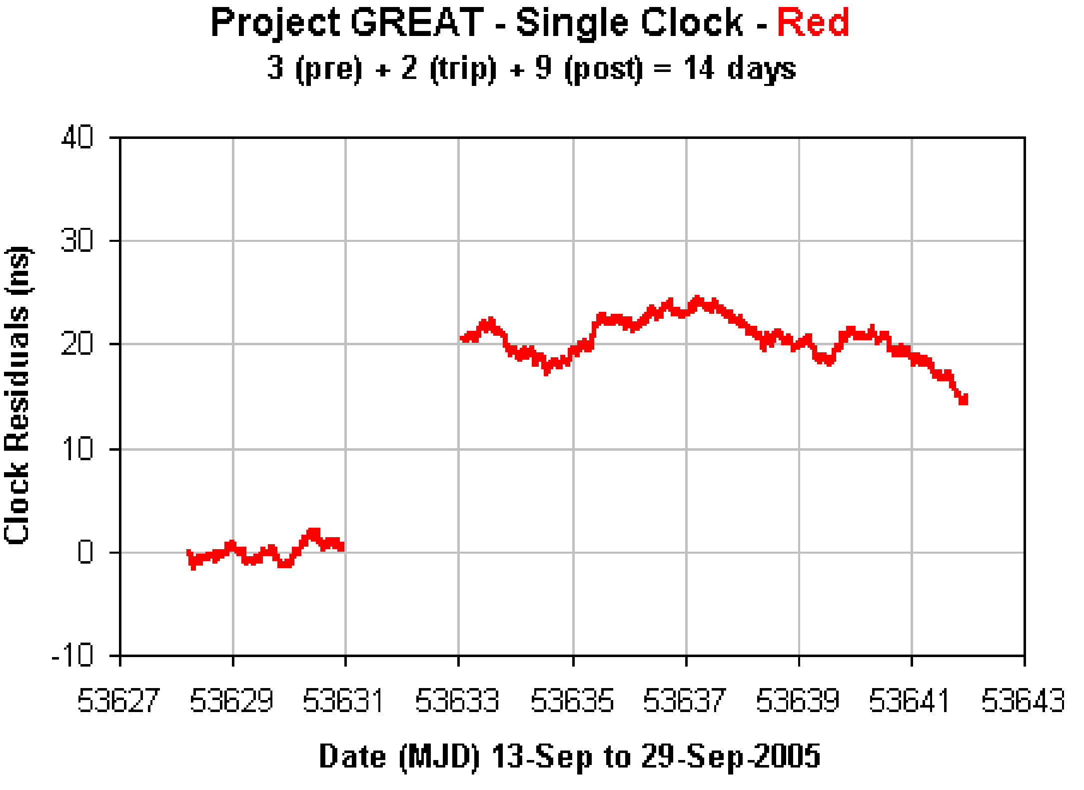
Elevation and *predicted* dilation



Clock time results

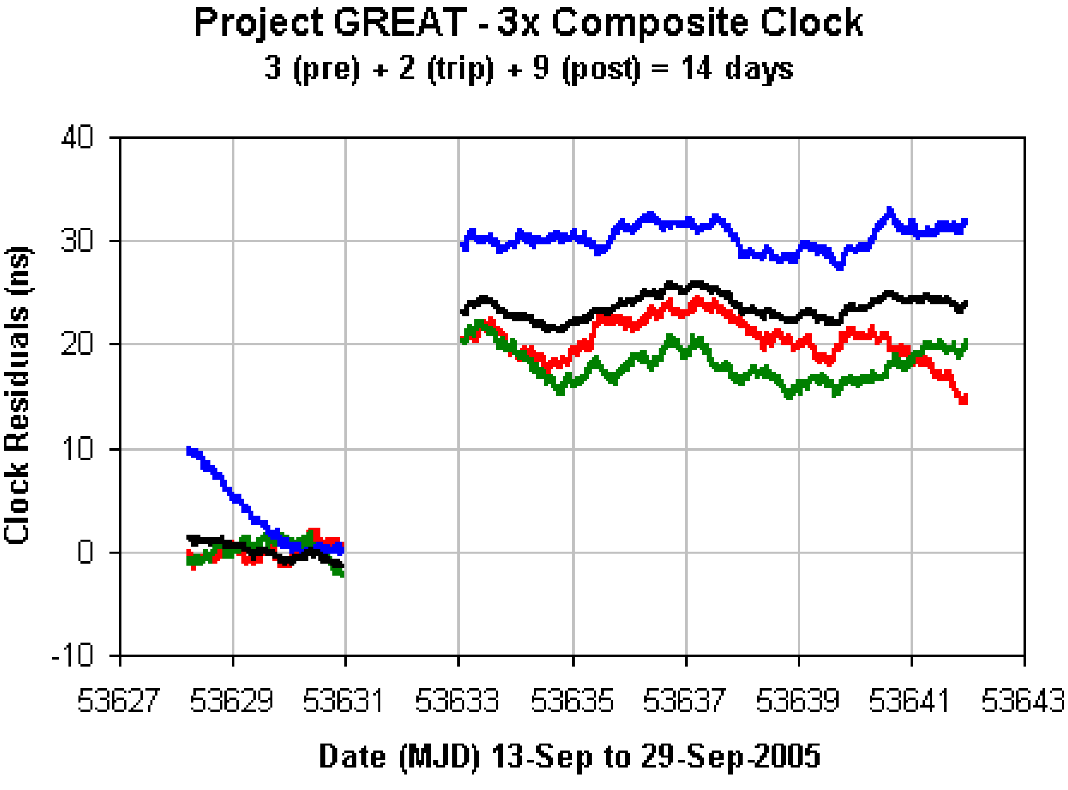
- Red
  20.3 ns





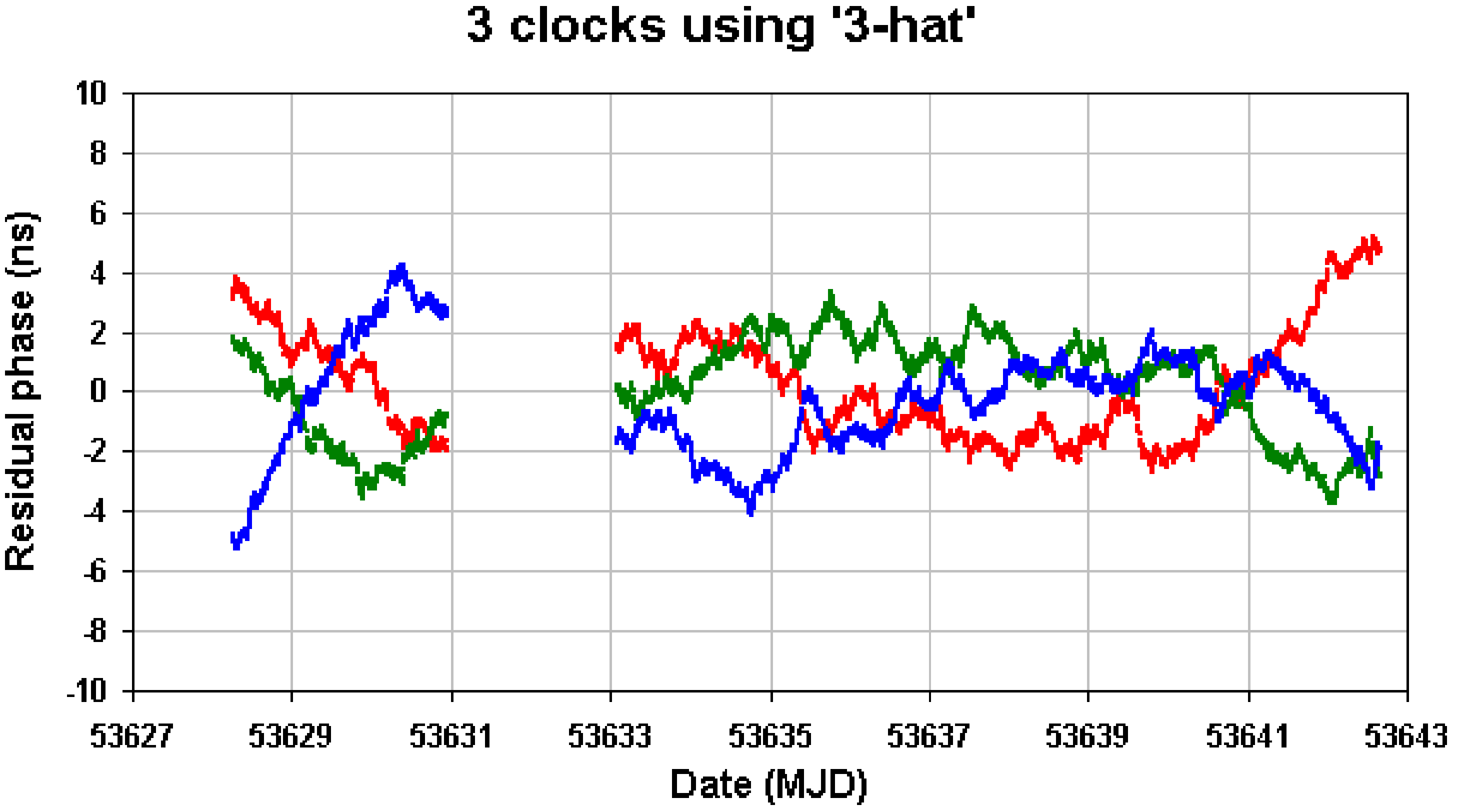
Clock time results (mean)

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



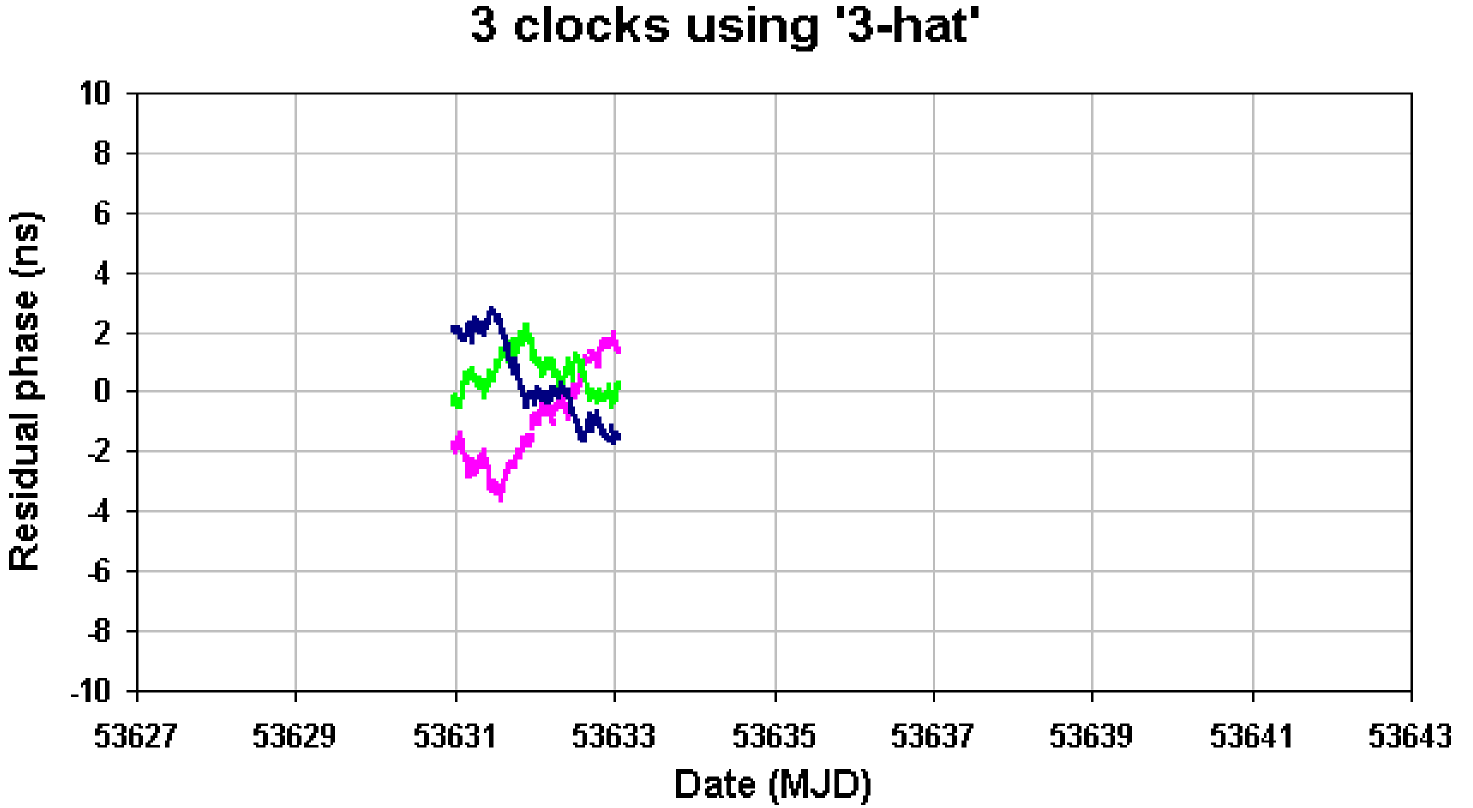
3-hat, residuals (home)

- $Cs_i - Cs_j$ via lab reference



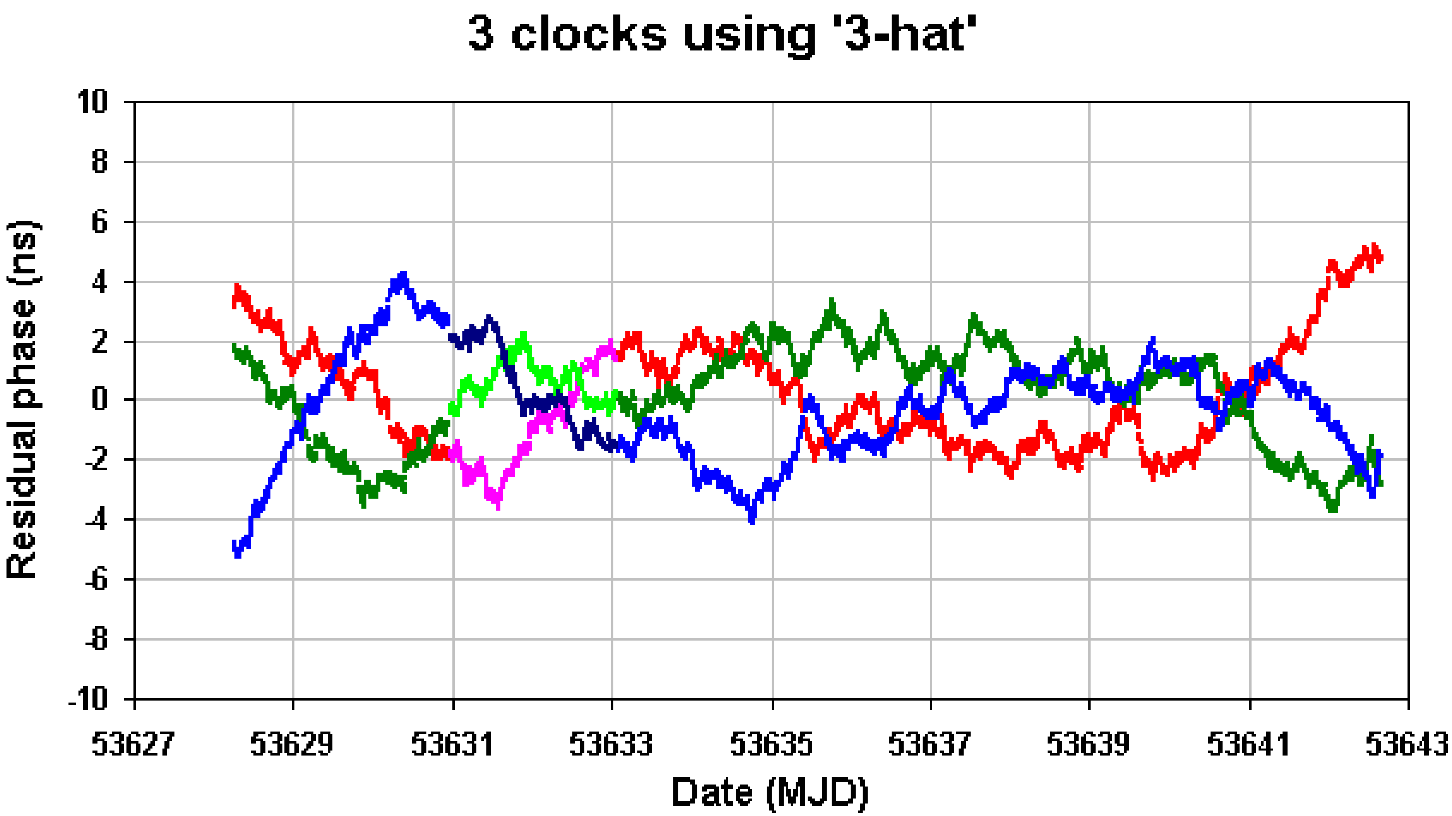
3-hat, residuals (away)

- Cs_i – Cs_j via mutual-comparisons

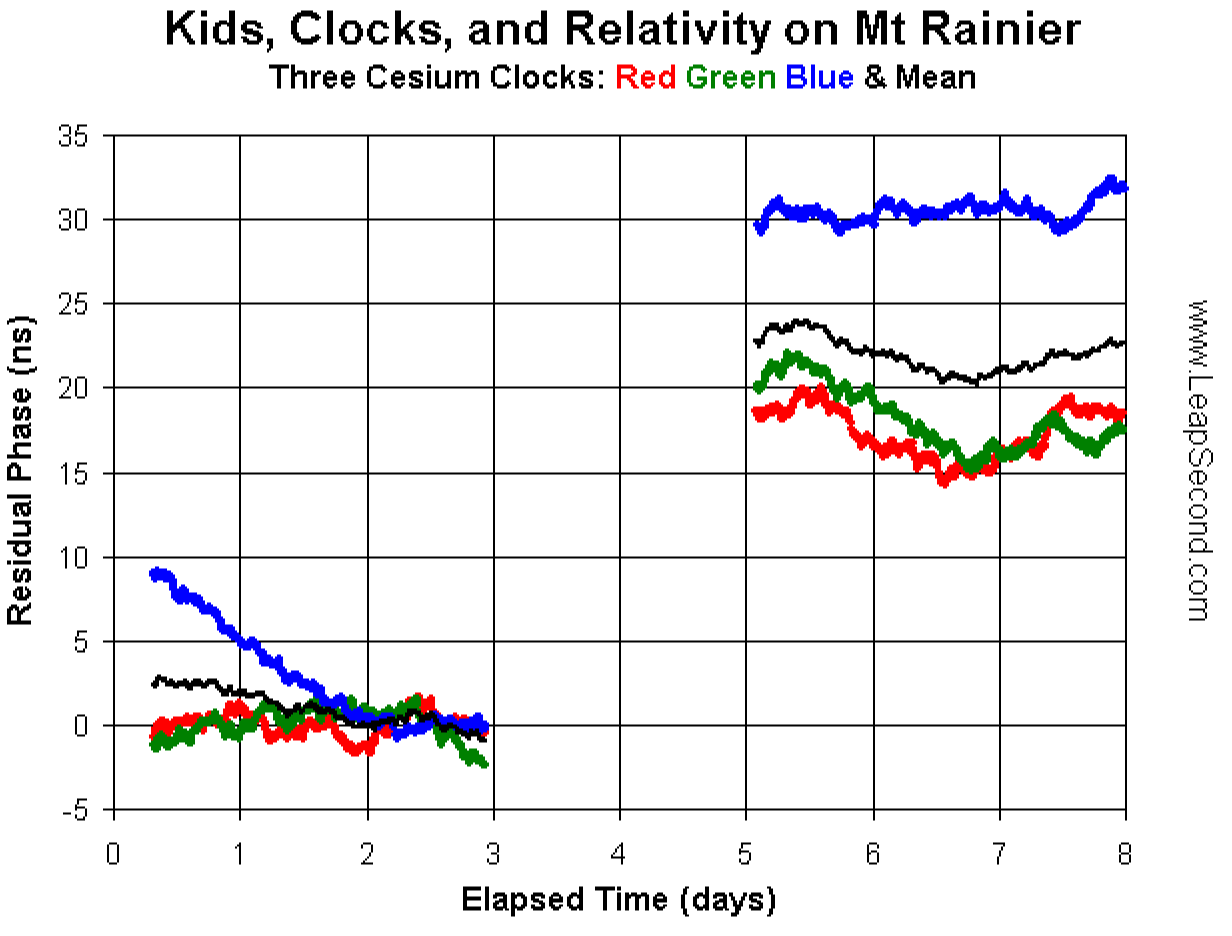


3-hat, residuals (combined)

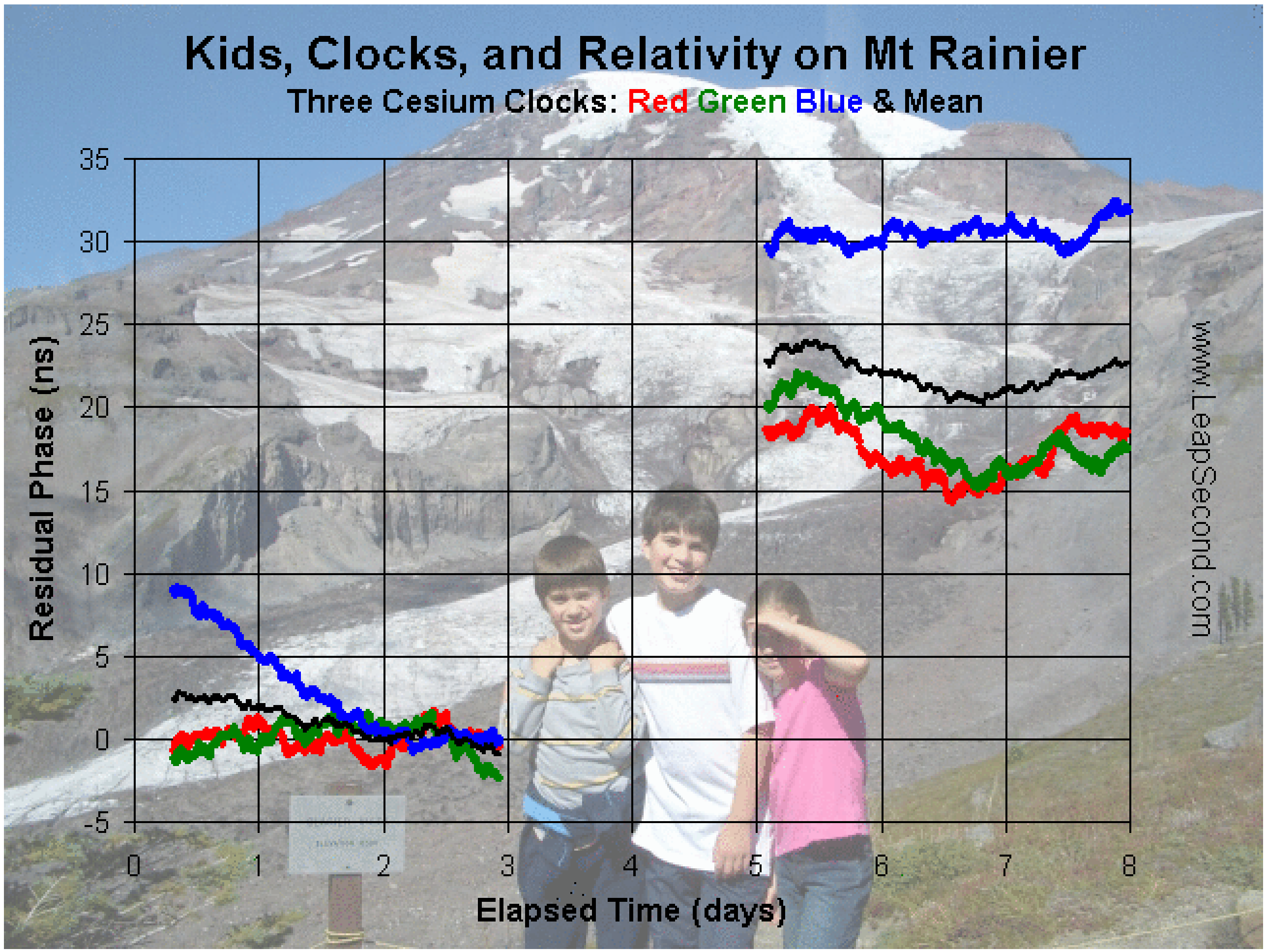
- $Cs_i - Cs_j$



Final graph (3+2+3 days)



Final graph (3+2+3 days)



Project GRE²AT – summary

- Theory of relativity confirmed by a family science experiment with cesium clocks
  – time dilation is real, just as Einstein predicted
  – came back tired and <u>22ns older</u>
- Atomic clocks are tomorrow's altimeters
  – what time is it?
  – what time *was* it?
  – *where* time *was* it?

Thank you!

- John Ackermann
- Steve Bible, Stan Horzepa, DCC
- *time-nuts* mailing list
- Contact: tvb@LeapSecond.com