GPS, Flying Clocks and Fun with Relativity

Tom Van Baak (tvb)

www.LeapSecond.com

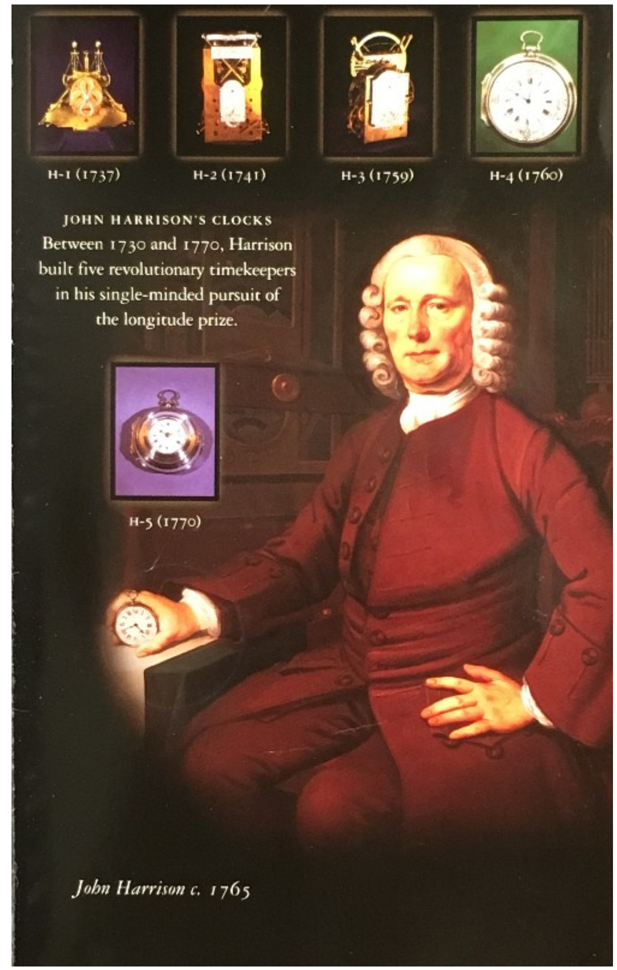
“Time Nut”

Outline

- Part 1 – Navigation and traveling clocks
    - clocks, timing, the ‘T’ in PNT
- Part 2 – GPS and relativity (time dilation)
    - so good it needs clock corrections
- Part 3 – Atomic clock collecting hobby
    - going to extremes at home
- Part 4 – Project GREAT
    - a DIY gravitational time dilation experiment

Chronometers at sea

- Who is this?
  - John Harrison
- Why all the clocks?
  - genius clockmaker
  - marine chronometer, accurate
- Longitude prize winner
  - 1759 (250+ years ago)
  - he put the “T” in PNT
- Read.the.book
  - by Dava Sobel



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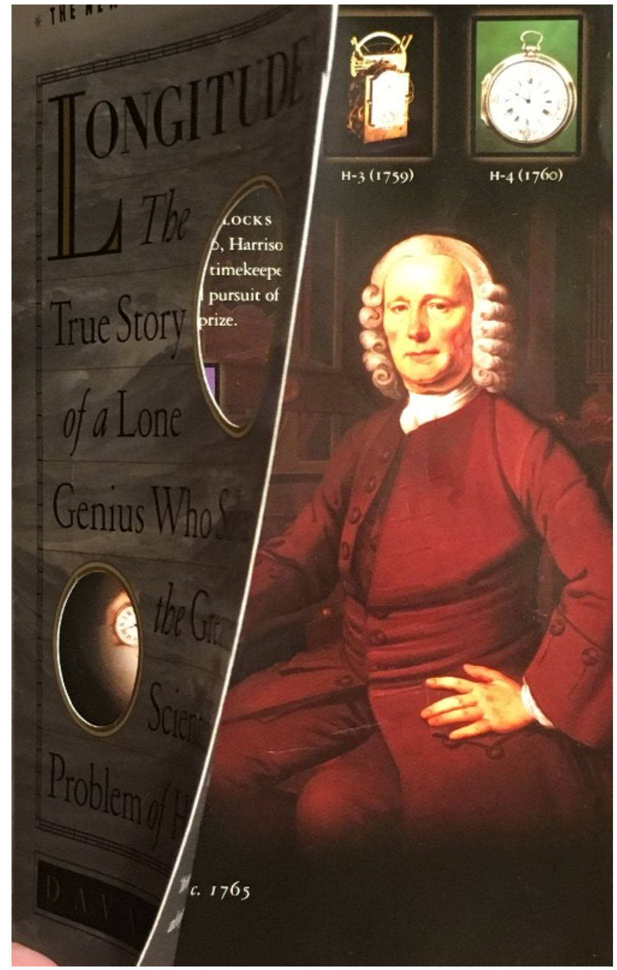

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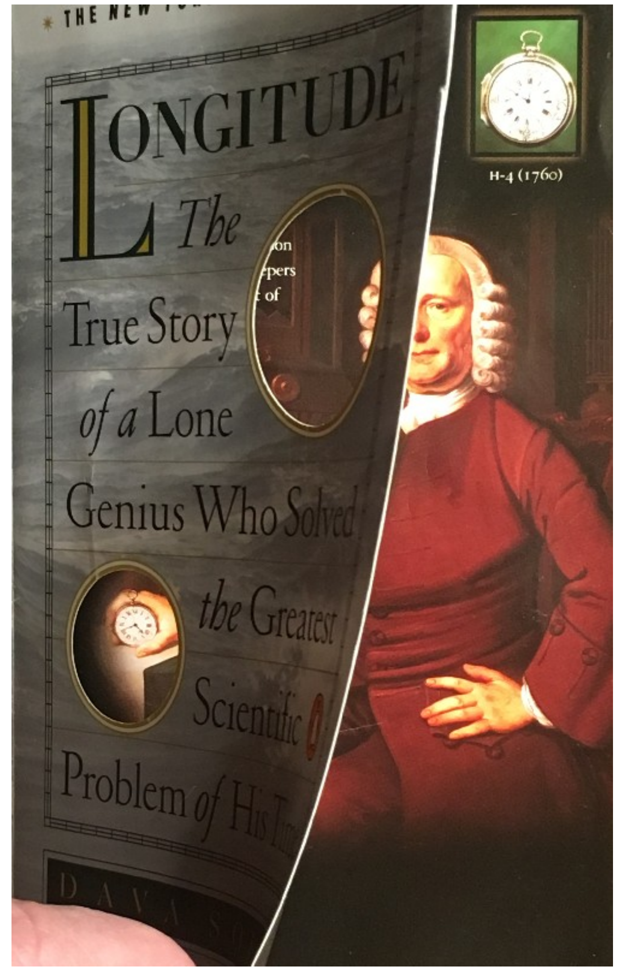

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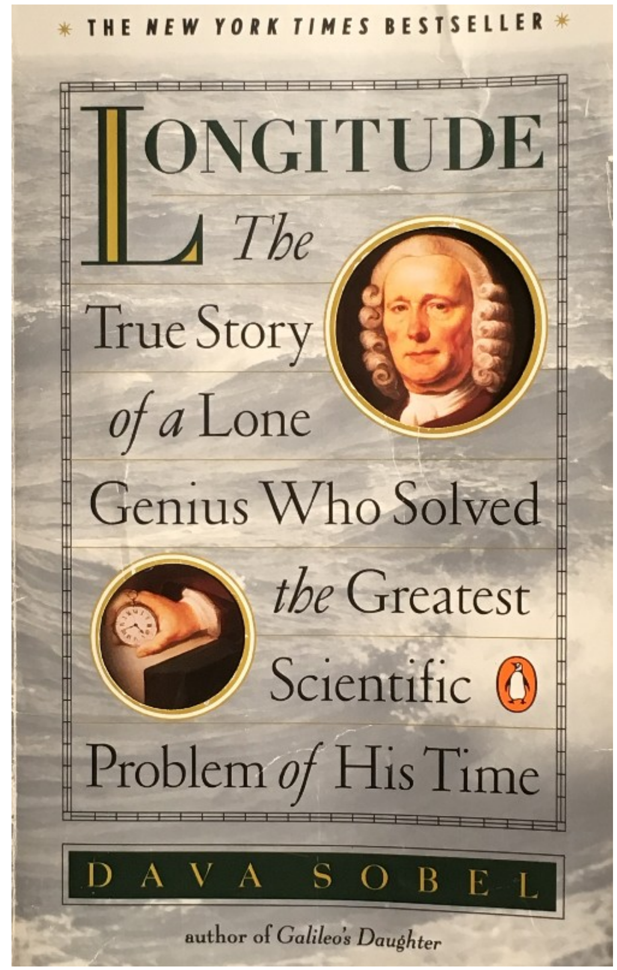
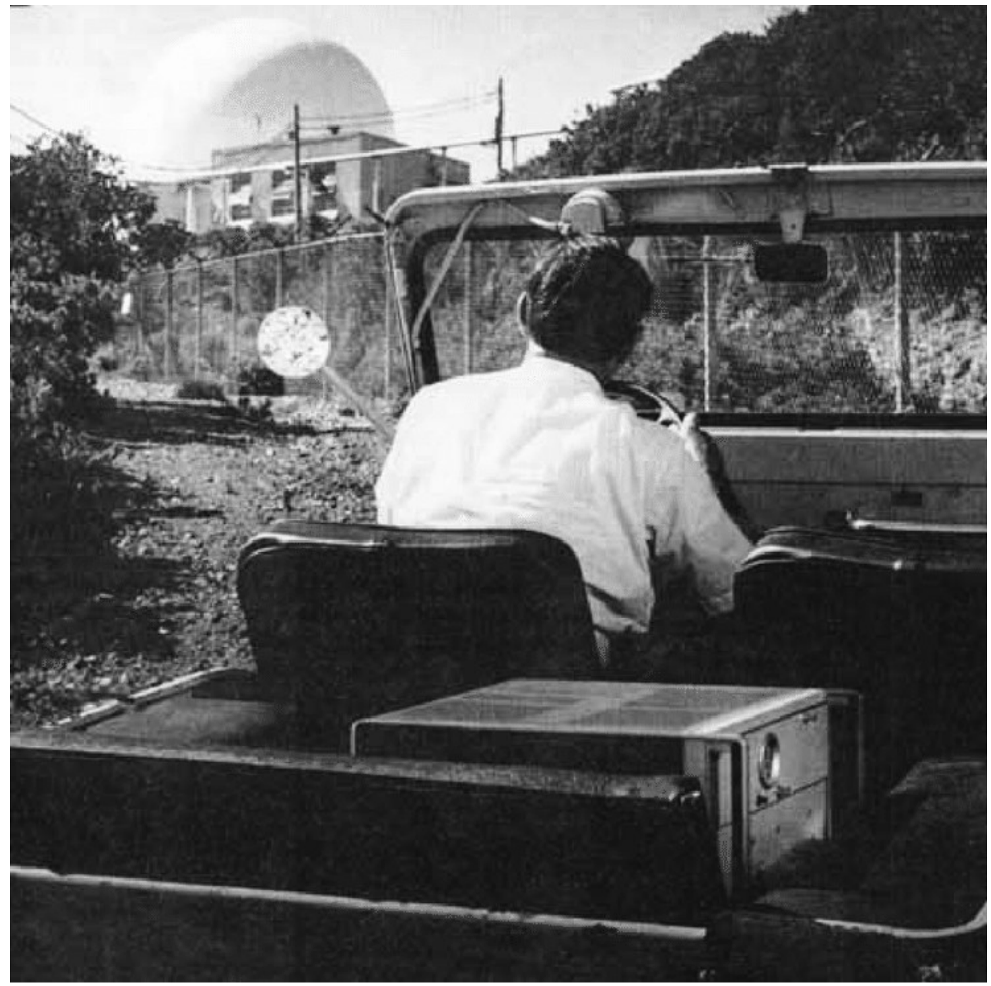


Cesium "chronometers" by air

- Who is this?
  - Len Cutler, *hp* clockmaker
- See the clock?
  - *hp* 5060A cesium atomic
  - batteries & "digital" clock
- Mission?
  - time synchronization
  - cross-country
  - round-the-world
  - 1960's "flying clock" era

Cesium “chronometers” by land

- Who is this?
  - *hp* field engineer
- See the clock?
  - *hp* 5061A cesium
  - atomic clock
- Marketing ad
  - year 1967
  - self-contained
  - portable, rugged
  - accurate 1μs/month



Flying clocks around-the-world

- Who is this?
  - J.Hafele & R.Keating
- See the clocks?
  - 4 @ *hp* 5061A
  - backup DC power
  - time interval counter
- Relativity experiment
  - year 1971
  - commercial flights
  - RTW, twice! (6 days)

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Ultimate “flying” clocks: spacecraft

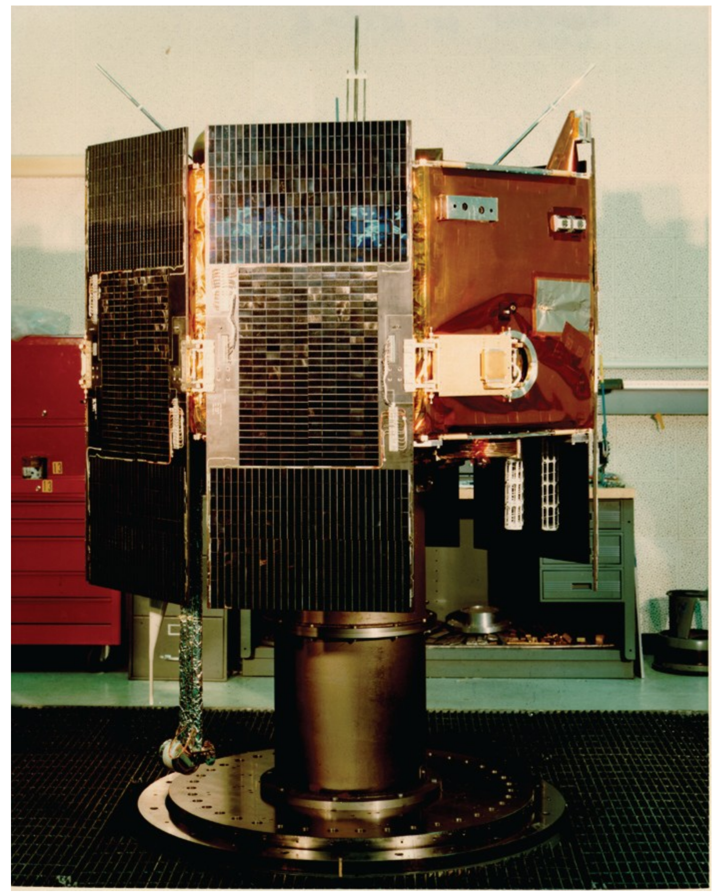
- GP-A
- NTS-2
- NAVSTAR / GPS

First space test was GP-A

- Gravity Probe "A"
- 1976, first H-maser in space
  - Robert Vessot, clockmaker
- Successful test of relativity
  - science mission
  - launched to 10,000 km
  - 2 hour flight up / down
  - 60 ppm accuracy

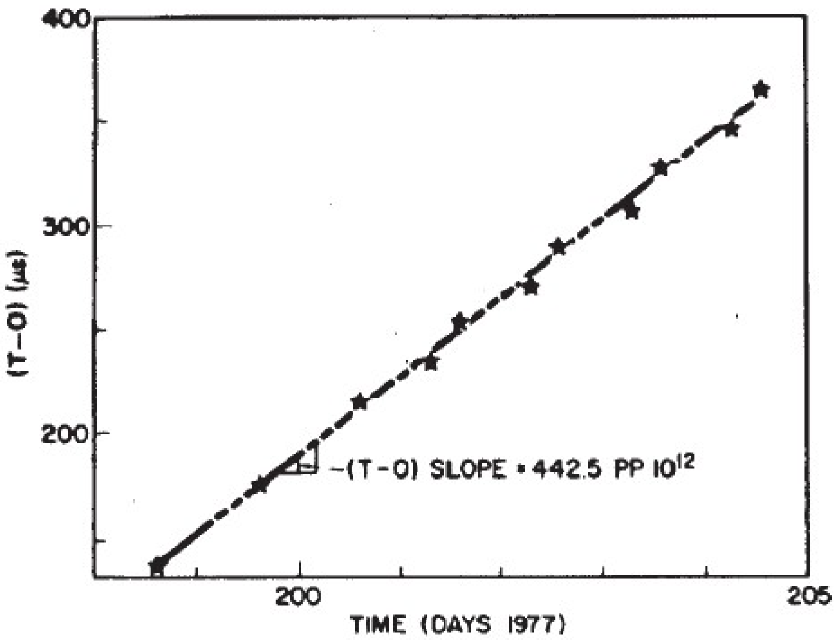
First orbital test was NTS-2

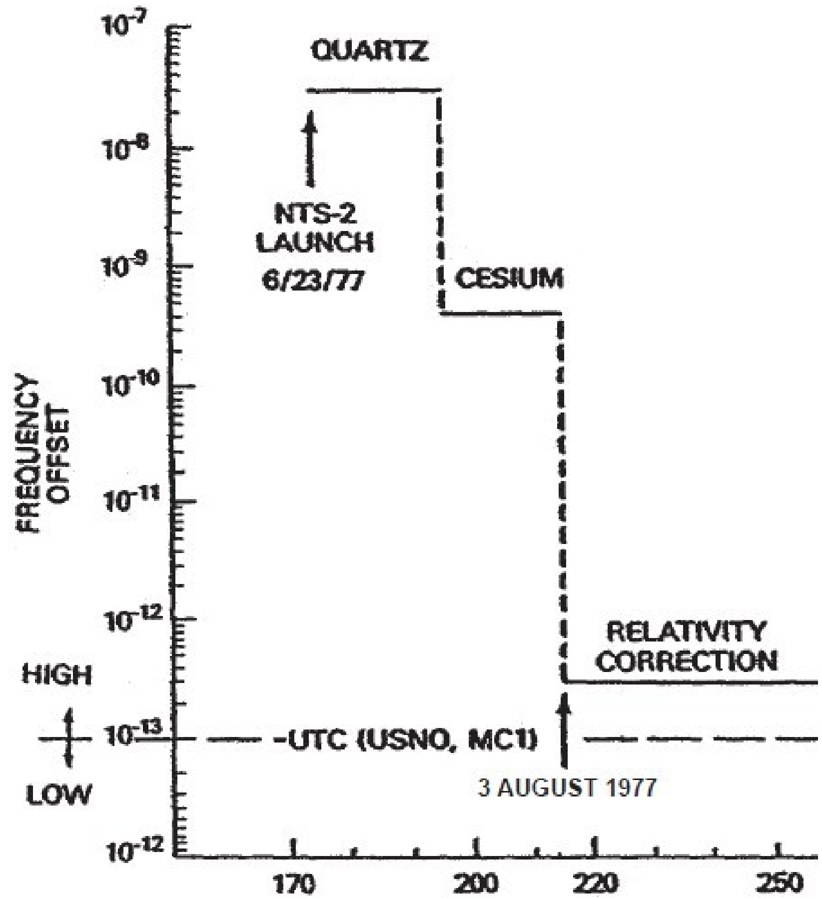
- “Navigation Technology Satellite”
- 1977, first cesium in orbit
  - Robert Kern, clockmaker
- Successful test of relativity
  - pre-NAVSTAR (GPS)
  - 12 hour orbit
  - similar relativity as GPS
  - cesium clocks, synthesizer



Relativity in NTS-2

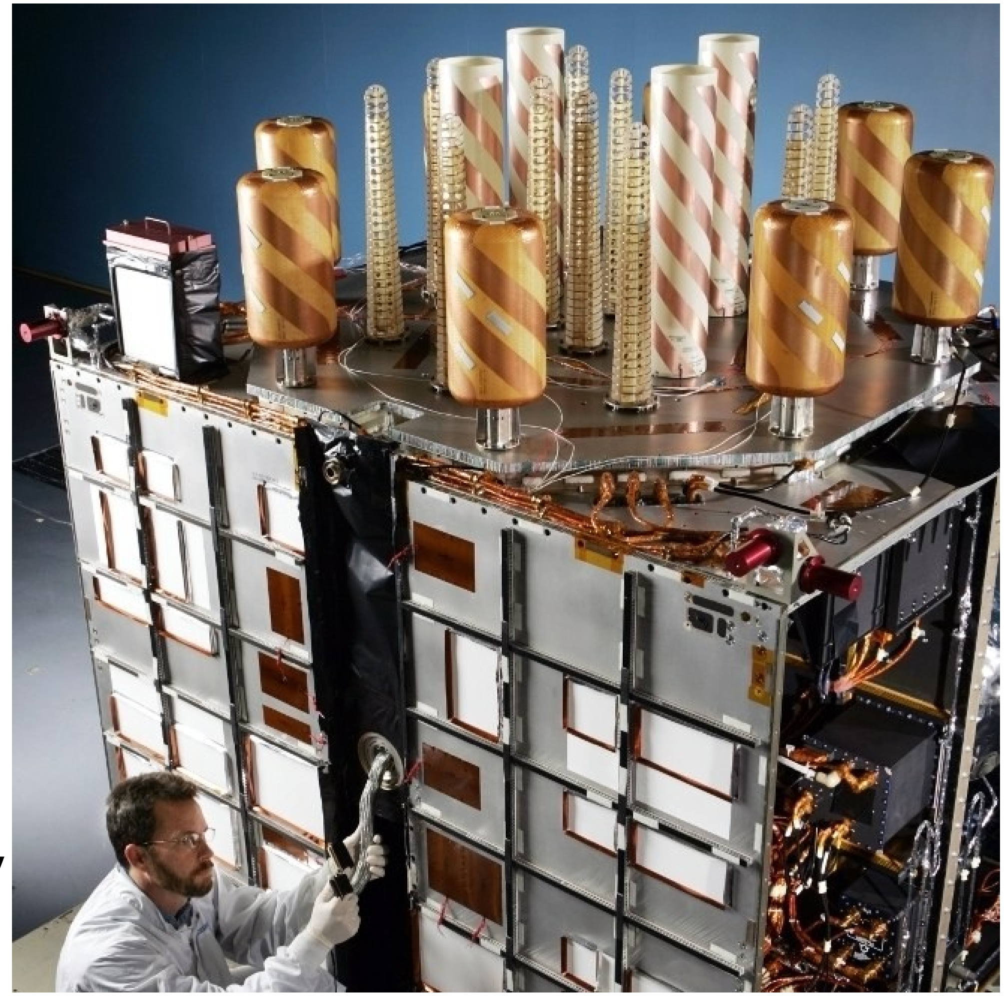
- Plots for NTS-2
- 4.425×10^{-10} = 38 μs/day





32 atomic clocks in space: GPS

- What's this?
  - GPS IIR-M
  - present era
- 250 year evolution
  - from Harrison to GPS
  - now many GNSS
- Clock accuracy
  - from seconds/day to nanoseconds/day



Relativity in GPS

- GPS orbits are extreme:
  speed 14,000 kph, 8,700 mph (Mach 12)
  altitude 20,000 km, 12,500 miles (~3× R_e)
  N.B. GPS speed is only 0.000013 c, "13 μc"
- Large relativistic effects occur:
  $\Delta f/f$ is -8.4×10^{-11}, or −7.3 μs/day (kinematic)
  $\Delta f/f$ is $+5.3\times10^{-10}$, or +45.6 μs/day (gravitational)
  $\Delta f/f$ is $+4.4\times10^{-10}$, or +38.3 μs/day (net effect)
  1.023 MHz set to 10.2299999954326 MHz

How small is 4×10^{-10} ?

- Relativity correction:
  - 4.4647×10^{-10} (fractional frequency offset)
  - 38.575 µs / day (time interval ratio units)
  - ~1 ms / month
  - 1 s / ~71 years
- In “newspaper” units:
  - ~6 inches / distance to Moon
  - ~1 atom / 1 meter
  - ~1.4 m^2 / area of Rhode Island
  - ~1 cm^3 / volume of Olympic swimming pool

Relativity at human scale: SR

- GPS velocity

  14,000 kph, 8,700 mph (Mach 12)

  $\Delta f/f$ is -8.4×10^{-11}, or −7.3 μs/day (kinematic)

- Human-scale velocity

  -3×10^{-13}, 0.02 μs/day – flying (500 mph)

  -4×10^{-15}, 0.0003 μs/day – driving (60 mph)

  -1×10^{-17}, 0.0000008 μs/day – walking (3 mph)

Relativity at human scale: GR

- GPS altitude
  - 20,000 km, 12,500 miles (~3× R_e)
  - $\Delta f/f$ is $+5.3\times10^{-10}$, or +45.6 μs/day (gravitational)
- Human-scale altitude
  - $+9.6\times10^{-13}$, 0.083 μs/day – Mt. Everest (8848 m)
  - $+1.7\times10^{-13}$, 0.015 μs/day – Denver, CO (1 mile)
  - $+9.5\times10^{-15}$, 0.00082 μs/day – Hoover tower (285 ft)
- "down to earth" relativity
  - Denver 3000× less than GPS

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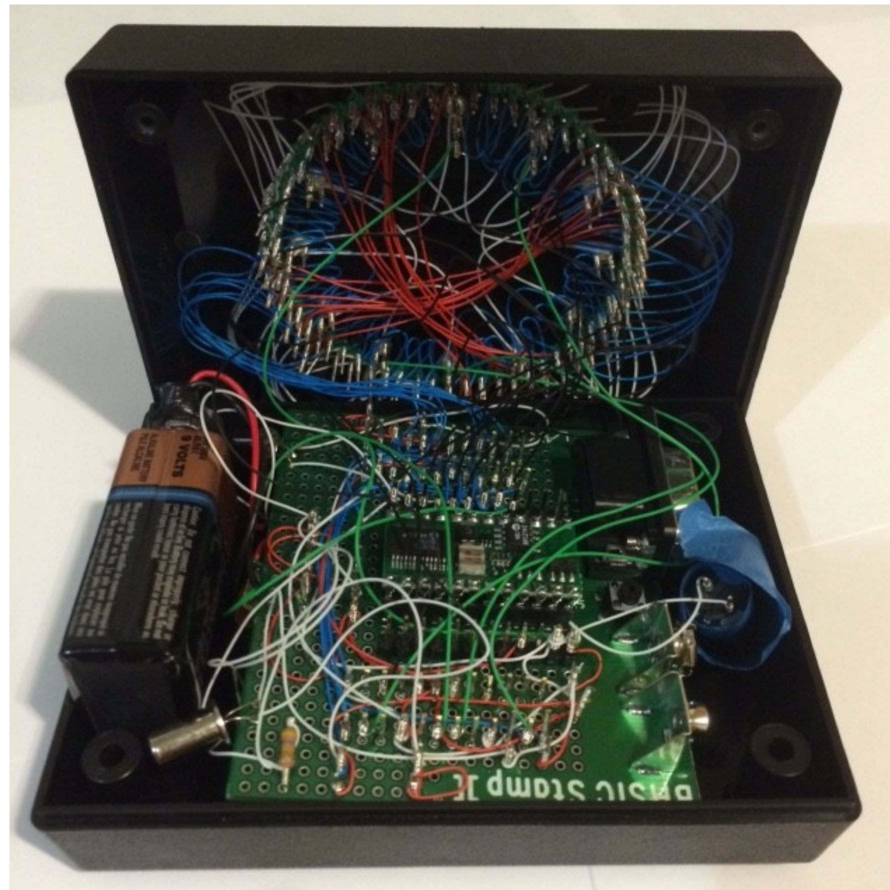
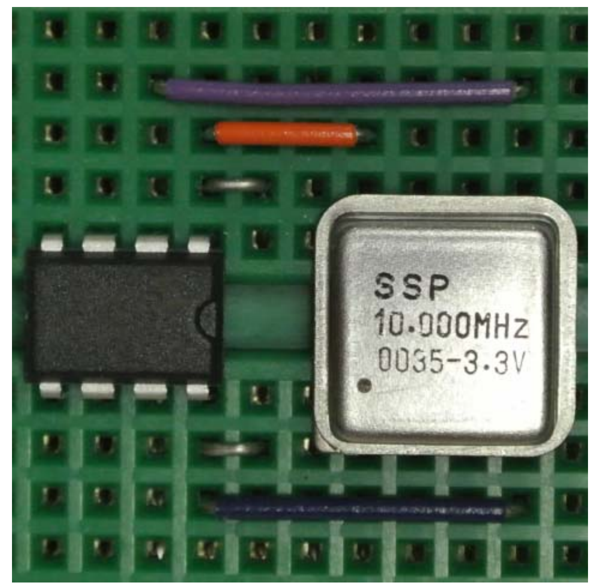
Precise time as a hobby (1994)



How to keep time?

- “Timebase” required (quartz oscillator)
  - how accurate is it?
  - how to measure it?
- Use frequency counter
  - how accurate is it?
  - how to measure it?
- Use a reference standard
  - how accurate …

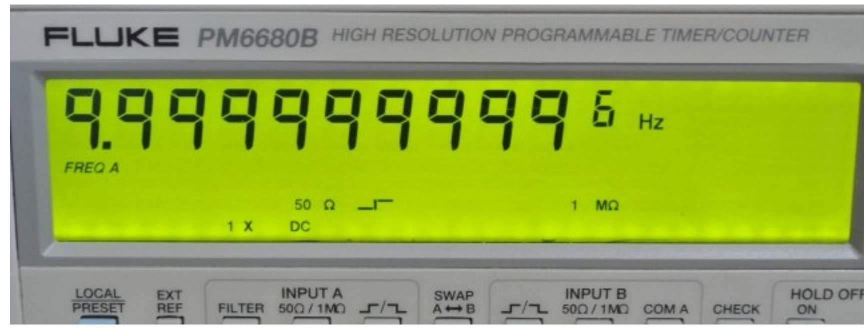


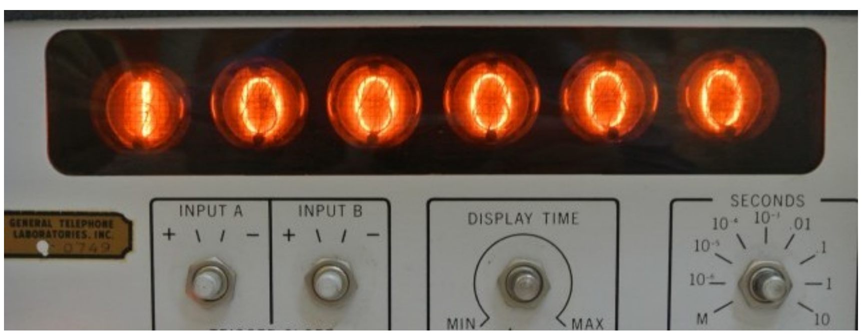
Timebase accuracy

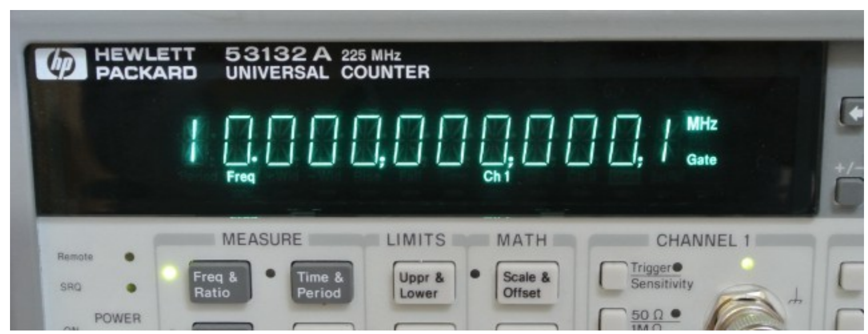
- 0.01 / 10.00 MHz = 0.1% (90 sec/day)
- 0.0001 / 10 MHz = 10 ppm (1 sec/day)

The quest for better oscillators

The quest for more digits







The quest for larger time lab

Slippery slope!

- I started www.LeapSecond.com
  - to share photos, data, software, lab reports, manuals
- Then created the "*time-nuts*" mailing list
  - now 1800 'nuts interested in amateur precise time
  - like amateur astronomy, seismology, etc.
- Relatively inexpensive, *time*-consuming hobby
  - measurement concepts work at $1 as well as $1000
  - easy to buy, repair, trade, collect interesting gear
  - massive trove of military and telecom surplus (eBay)

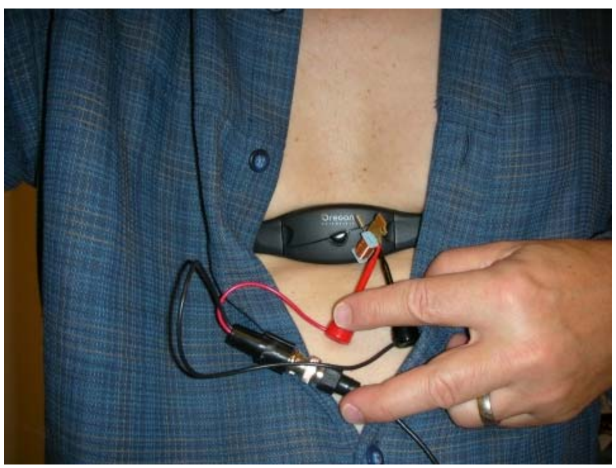
Vintage *hp* 5061A (eBay)

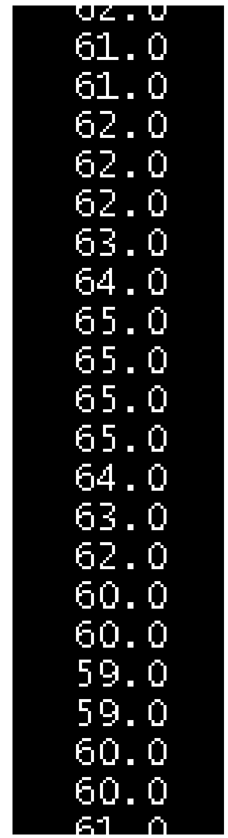
Extremely wide range of precision

- 10^{-2} = 1% ≈ 15 min / day
- 10^{-4} = 0.01% ≈ 1 min / week
- 10^{-6} = 1 ppm ≈ 0.1 s / day
- 10^{-8} ≈ 1 ms / day
- 10^{-10} ≈ 10 μs / day
- 10^{-12} = 1 ppt ≈ 100 ns / day
- 10^{-14} ≈ ~1 ns / day ≈ 1 s / 3,000,000 years
- 10^{-16} ≈ ~3 ns / year ≈ 3 s / billion years

10^{-2} heart beat

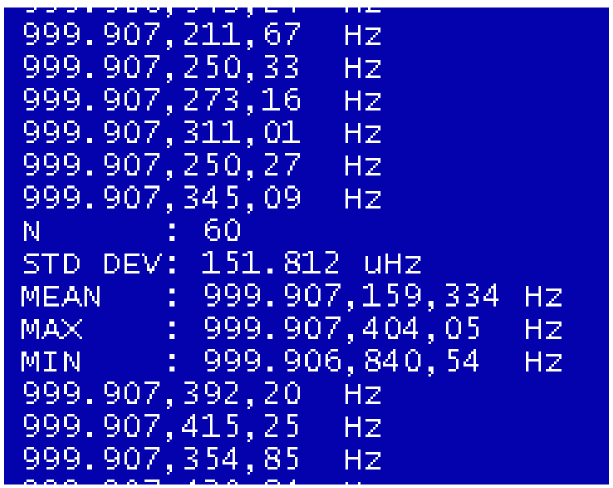
- The original ‘1 PPS’
- 10% stability at night, long-term
- 1% stability possible, short-term

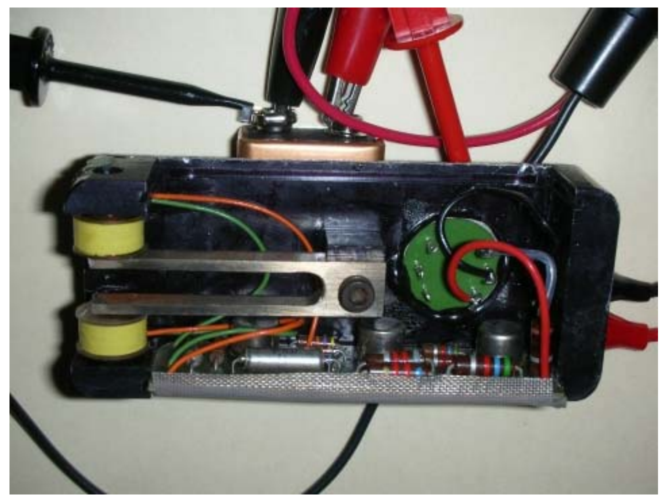




10^{-4} tuning fork, mains

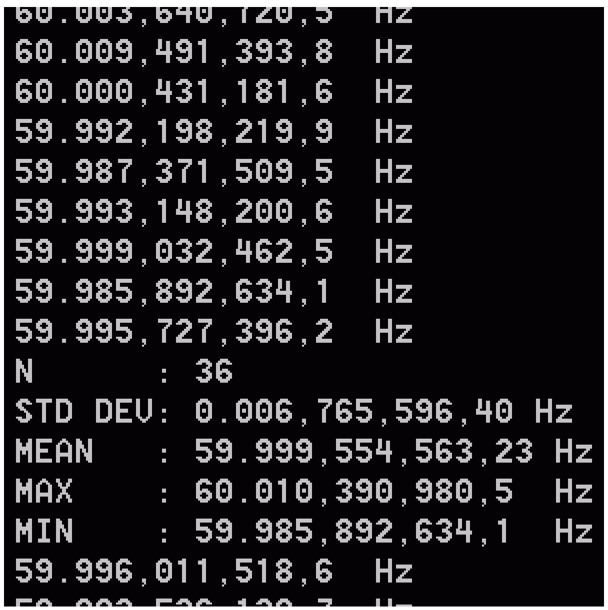
- Mechanical oscillator transistorized
- “Four 9’s”

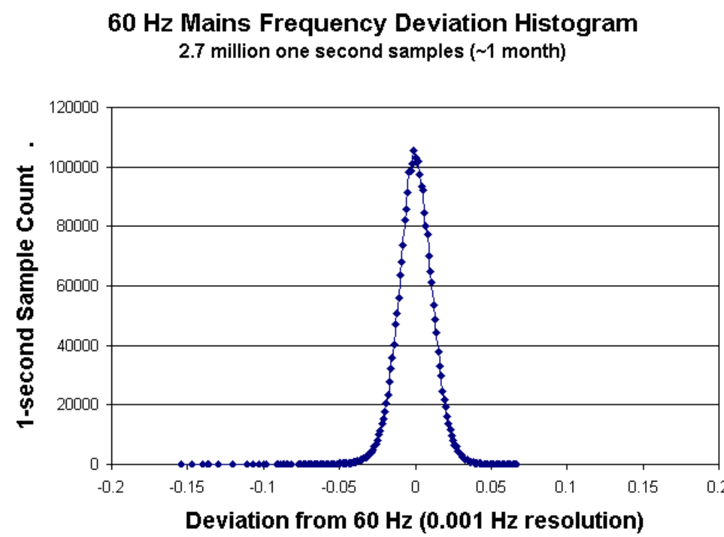




10^{-4} tuning fork, mains

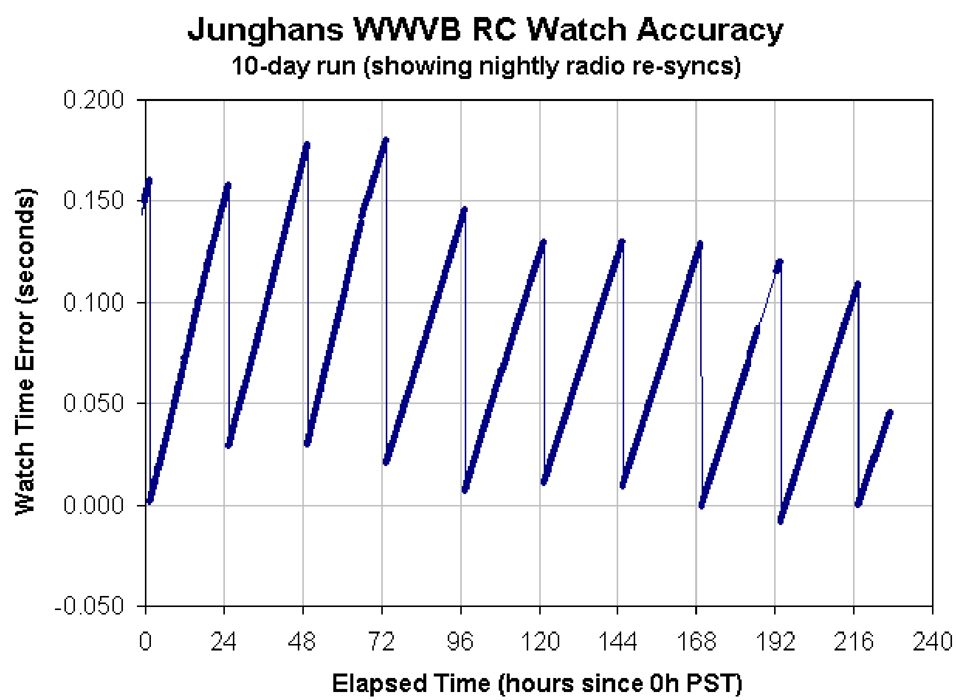
- Power line frequency: 60± Hz





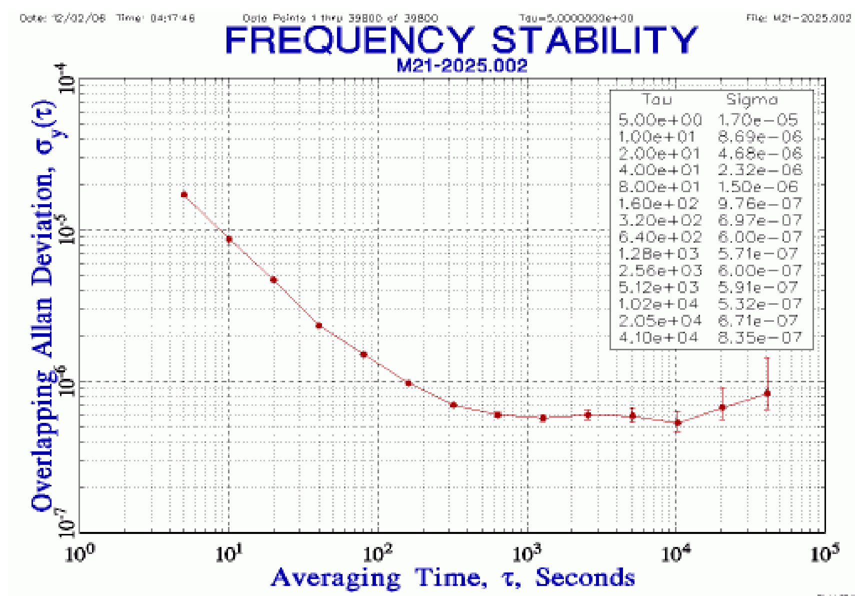
10^{-6} quartz watch, chronometer

- +160 ms/d = +1.85 ppm



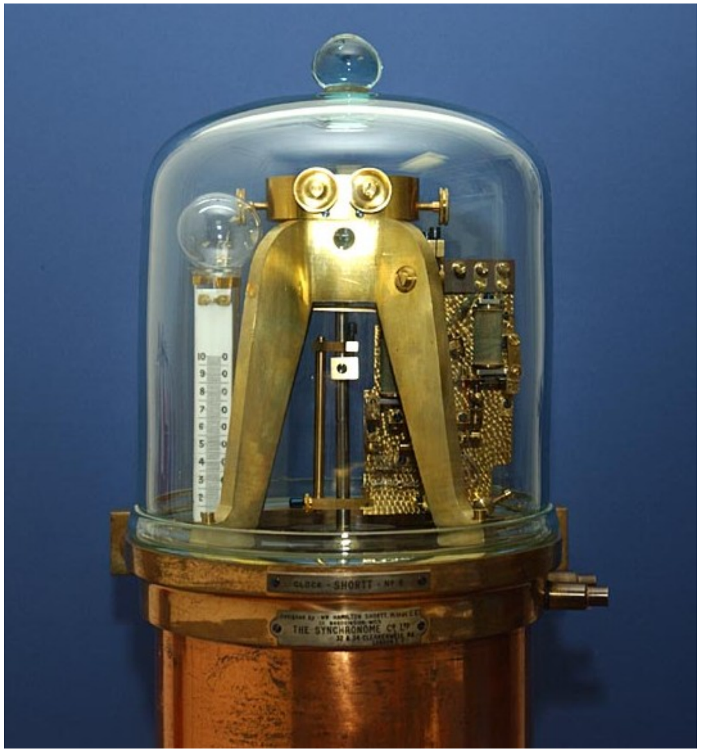
10^{-6} quartz watch, chronometer

- Conservatively rated ¼ sec/day deviation



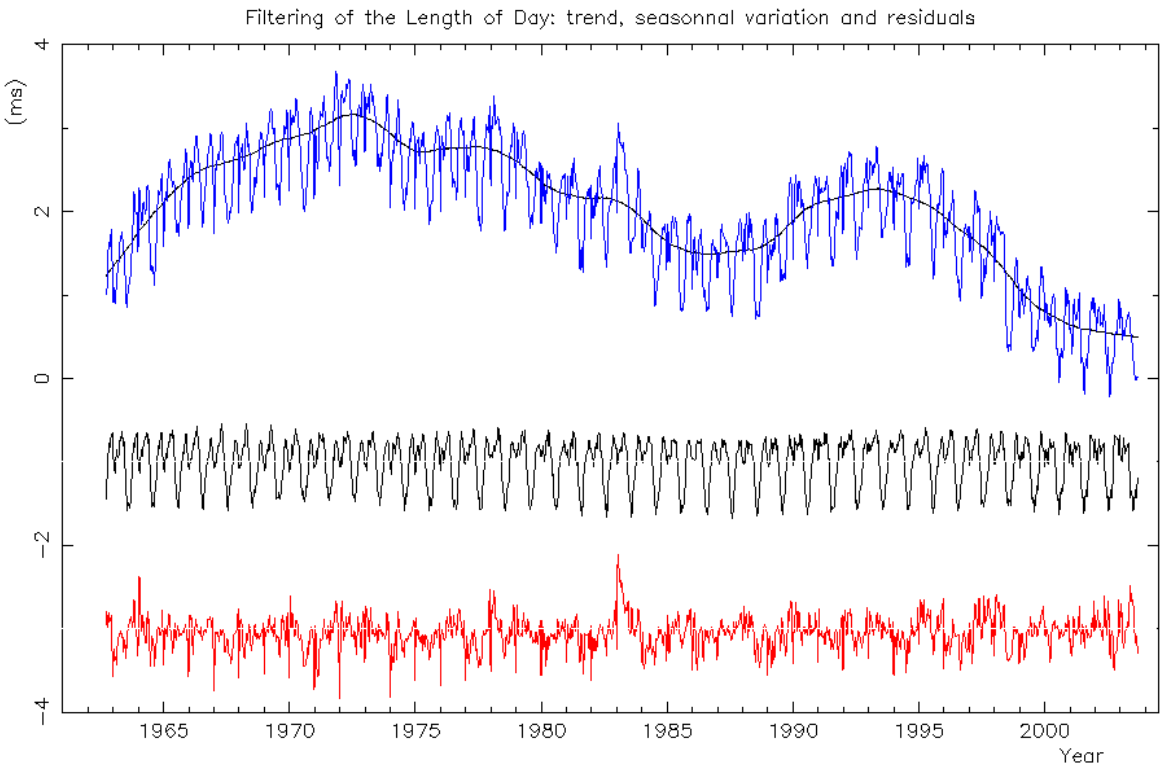
10^{-8} pendulum clock, earth

- Shortt-Synchronome
- 1 second / year



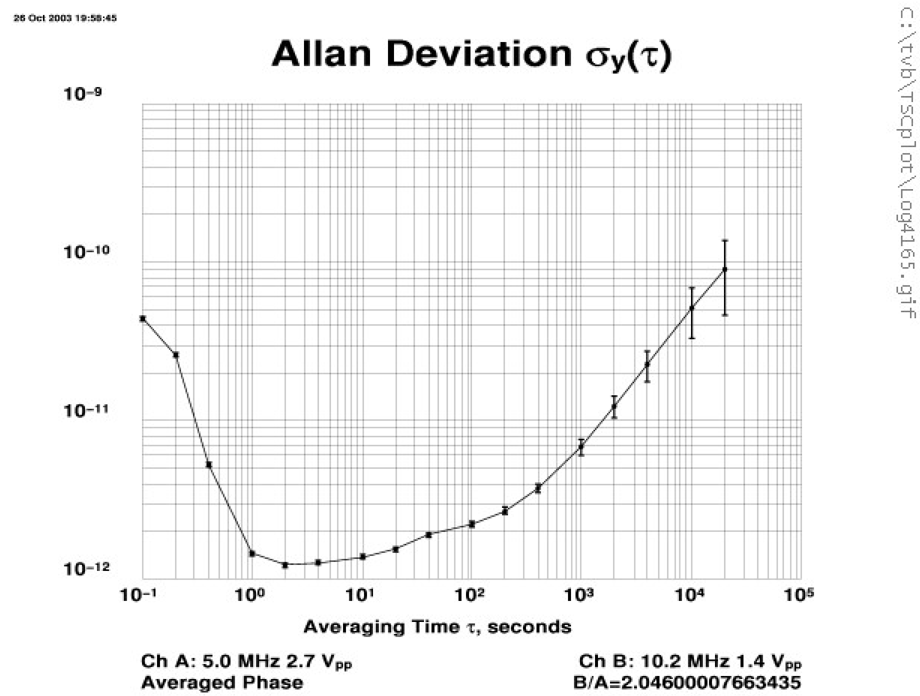
10^{-8} pendulum clock, earth

- ~1 second / year, irregular



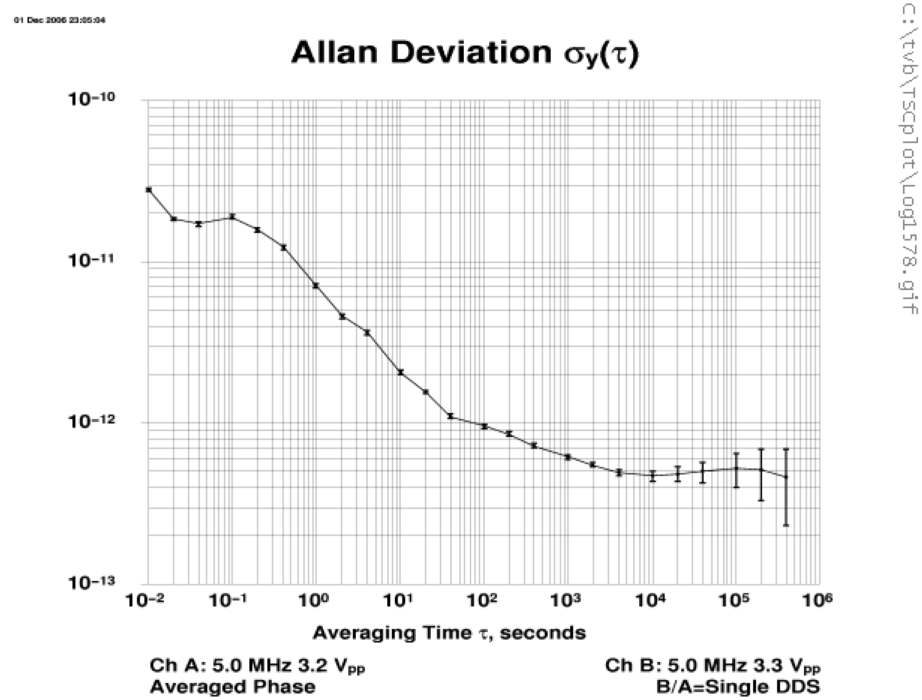
10^{-10} ovenized quartz

- $10^{-10} \ldots 10^{-13}$ short-term
- 5×10^{-10}/d drift



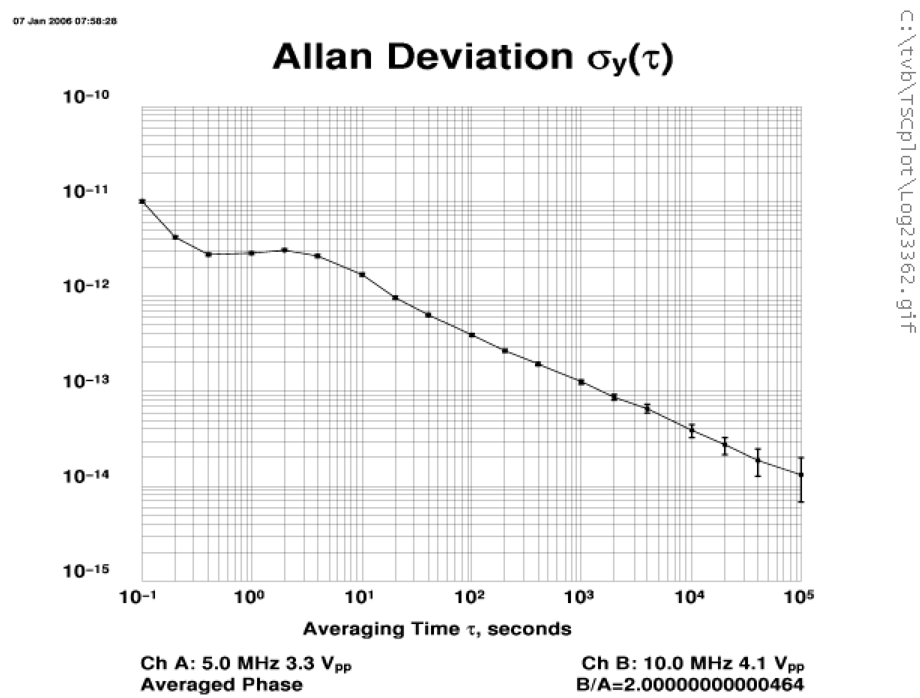
10^{-12} rubidium (atomic)

- ~10^{-13} mid-term
- ~10^{-11}/month drift



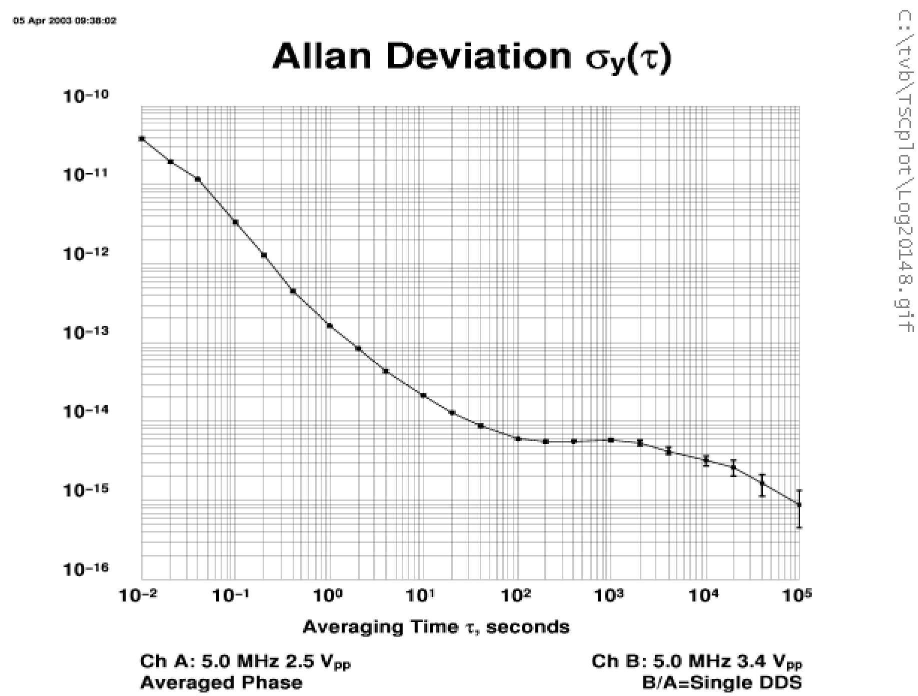
10^{-14} cesium (atomic)

- $\sim 10^{-13}$ mid-term
- 1×10^{-14} at 1 day



10^{-16} hydrogen maser

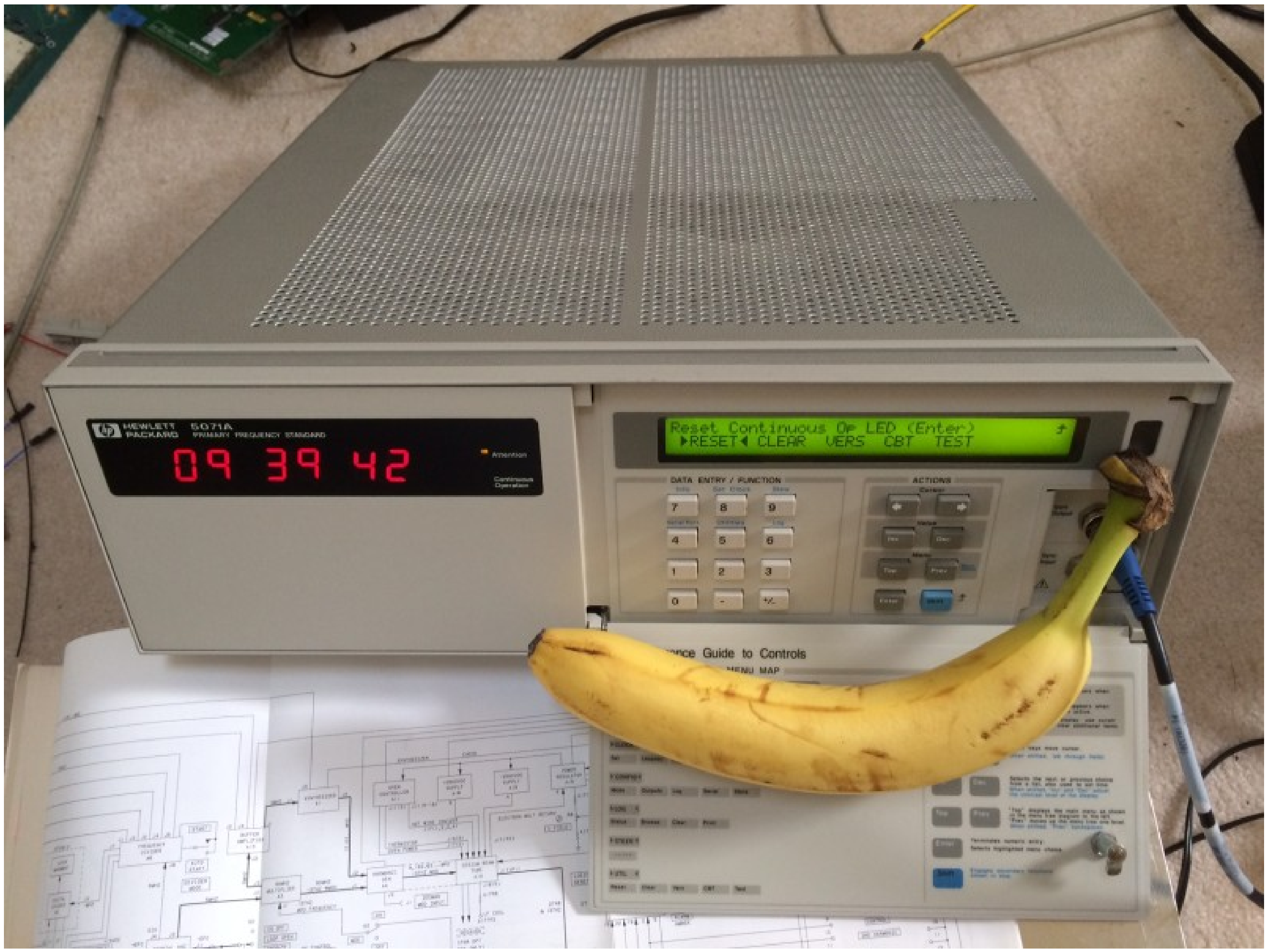
- Most stable (but non-portable)
- 5×10^{-16} possible



FYI: cesium (caesium)

- Cesium atomic clocks are ***not*** radioactive
- They use a natural, stable Cs^{133} atom, not the dangerous 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 [28 °C]

First radioactive cesium clock!



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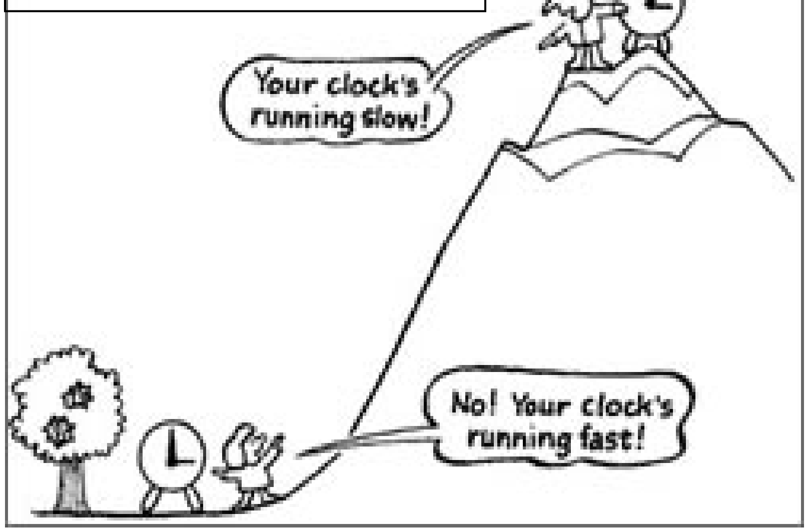
Clocks, mountains, relativity

- Is relativity detectable at human scale?
  - have I accumulated enough toys by now?
  - can time dilation be measured by an amateur?
  - can I travel fast enough, or high enough?

From NPL website

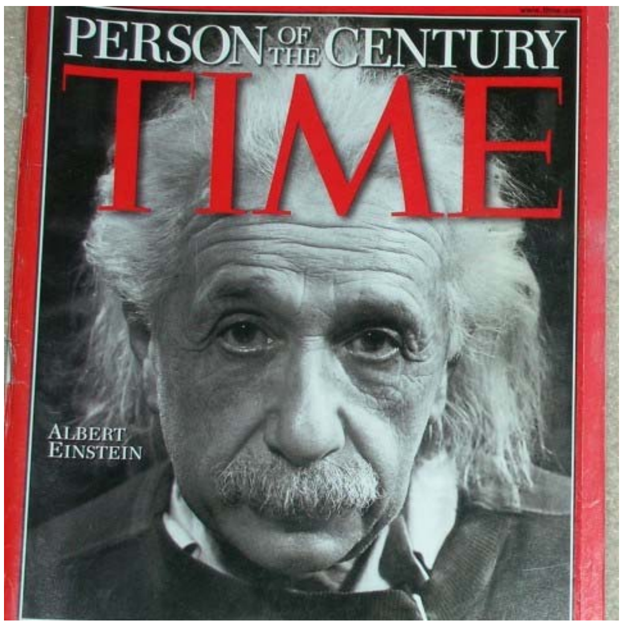


A great idea

- Take our 3 kids with *portable* <u>cesium</u> clocks high up Mt Rainier
- See if Einstein was right about *gravity* and *time*
- See if clocks really run <u>faster</u> up there
- In 2005

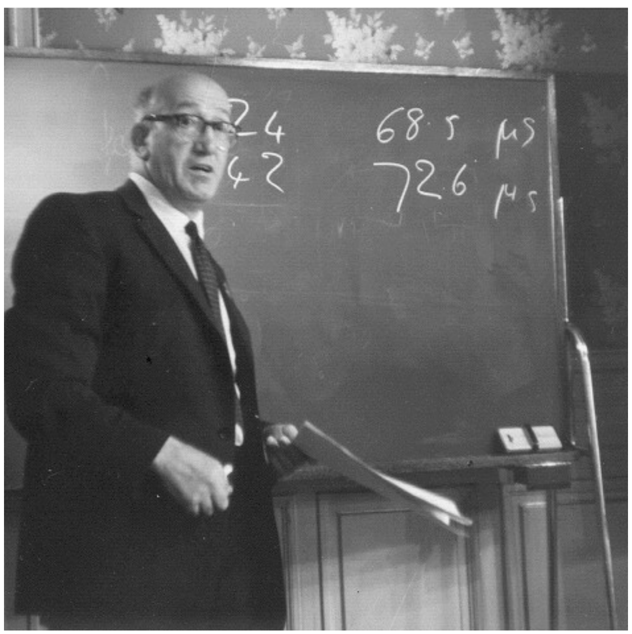
Einstein and 2005

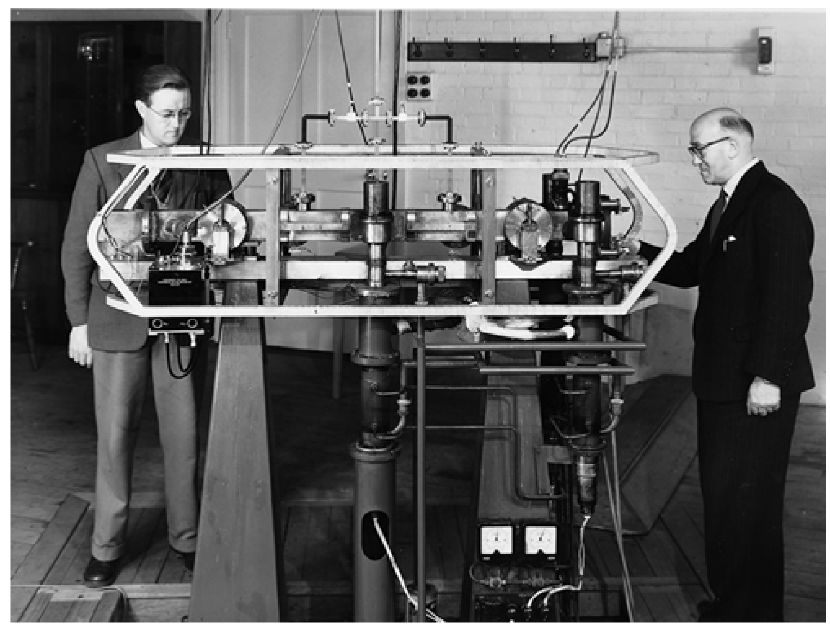
- 100th anniversary of relativity: books, magazines, radio, TV, web sites, "Physics Year", lectures…



Louis Essen (UK) and 2005

- 50^{th} anniversary of cesium clock (NPL)
- “famous for a second” 9 192 631 770 Hz





Project GRE^{2}AT

- 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
- First “home made” general relativity test

Back-of-envelope calculation

- Turn *infinitesimal* into *measurable*
- Frequency change $\Delta f/f \approx gh/c^2$

  $\Delta f/f \approx 1.09\times10^{-16}$ s/s/meter

- But if you go up 1 km instead of 1 m, then

  $\Delta f/f = 1.1\times10^{-13} = 0.11$ ps/s

  note: 4000× less than GPS

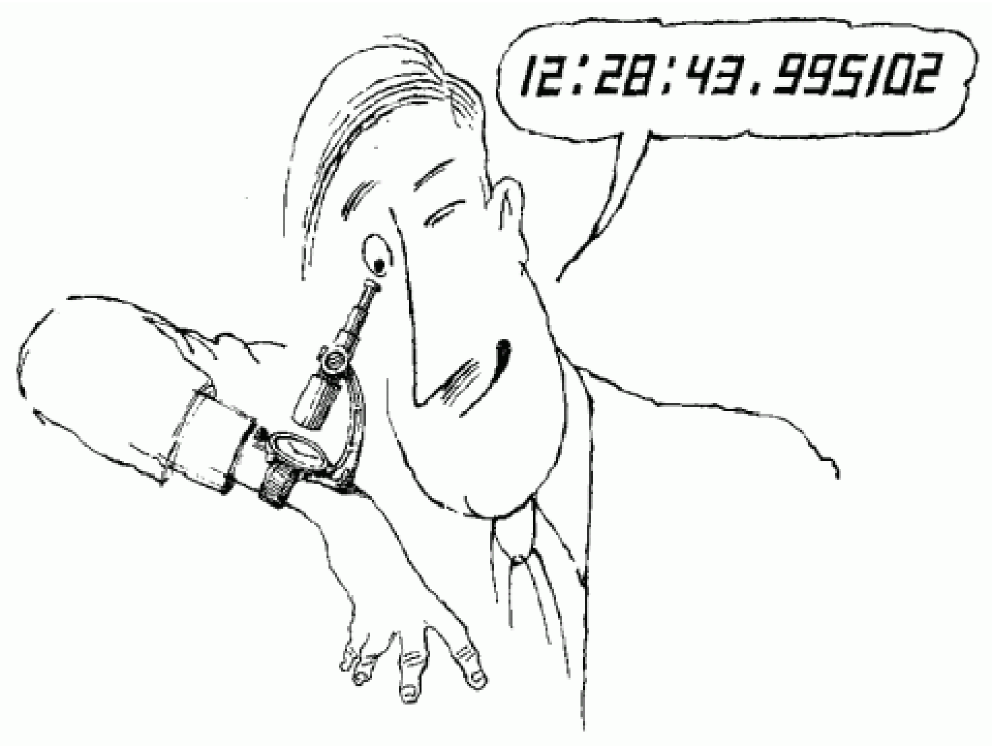
- And if you stay up there 24 hours, then

  $\Delta T = \Delta f/f \times 86400 \text{ s} = 9.5\times10^{-9} \text{ s} = 9.5$ ns

- Rule-of-thumb: 1 km elevation ≈ 10 ns/day

Magnify 0.000000000000000001

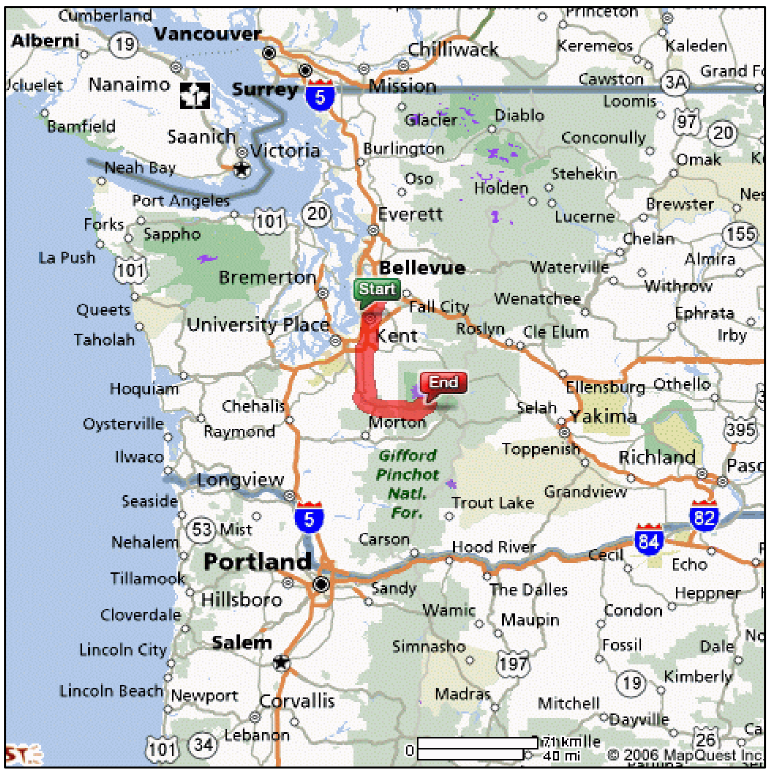
- Go as **high** as possible
- Stay as **long** as possible
- Measure as **precisely** as possible
- Use the **best** clock(s) possible

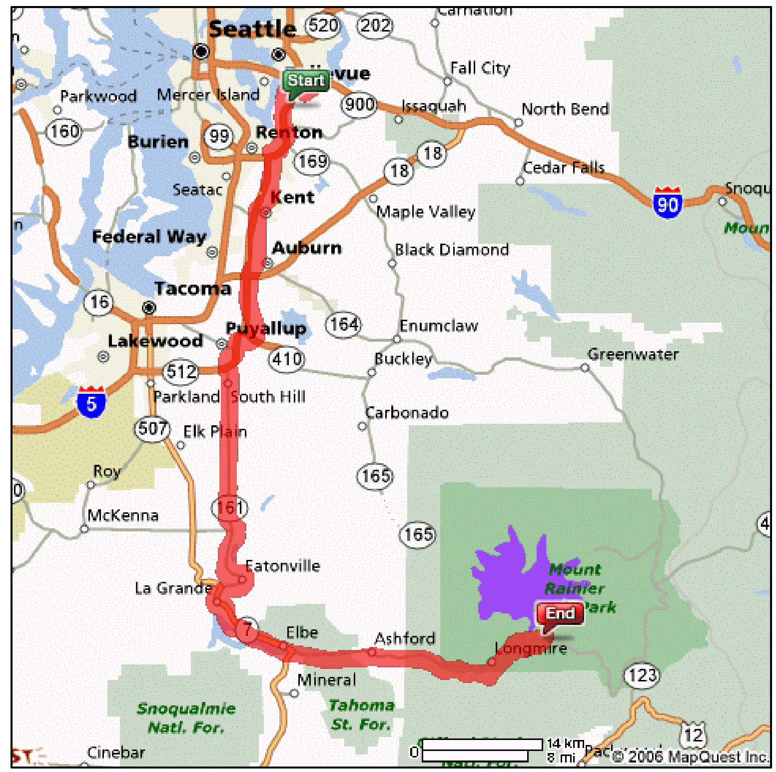


Cartoon by Dusan Petricic
Scientific American column Wonders by Philip and Phyllis Morrison
http://www.sciam.com/1998/0298issue/0298wonders.html

Bellevue to Mt Rainier

- Just 100 miles away (~2½ hours)



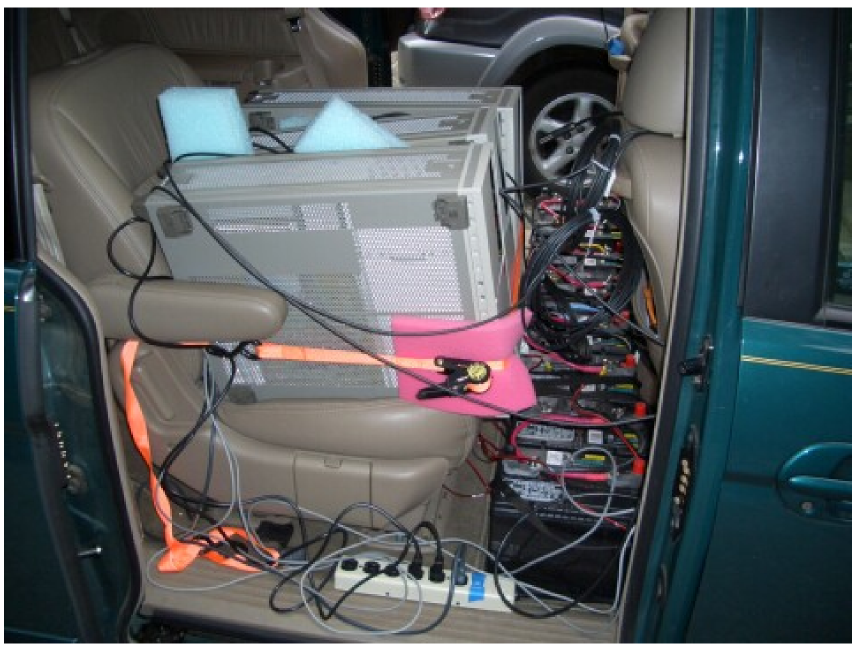


The GREAT trip, day 1

- Carrying synchronized, running cesium clock downstairs. Repeat. Repeat.

The GREAT trip, day 1

- 3 clocks in the middle. Batteries on the floor. Monitoring instruments in front.



The GREAT trip, day 1

- 3 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 2

- Paradise Inn is at 5400’ elevation. Large parking lot for car & precious clocks.

The GREAT trip, day 2

- Classic old Northwest inn. Wonderful place to visit during the summer.

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. Worried about running out of fuel.

The GREAT trip, day 3

- More hiking, exploring, playing. It’s a fun place for a weekend.

The GREAT trip, day 3

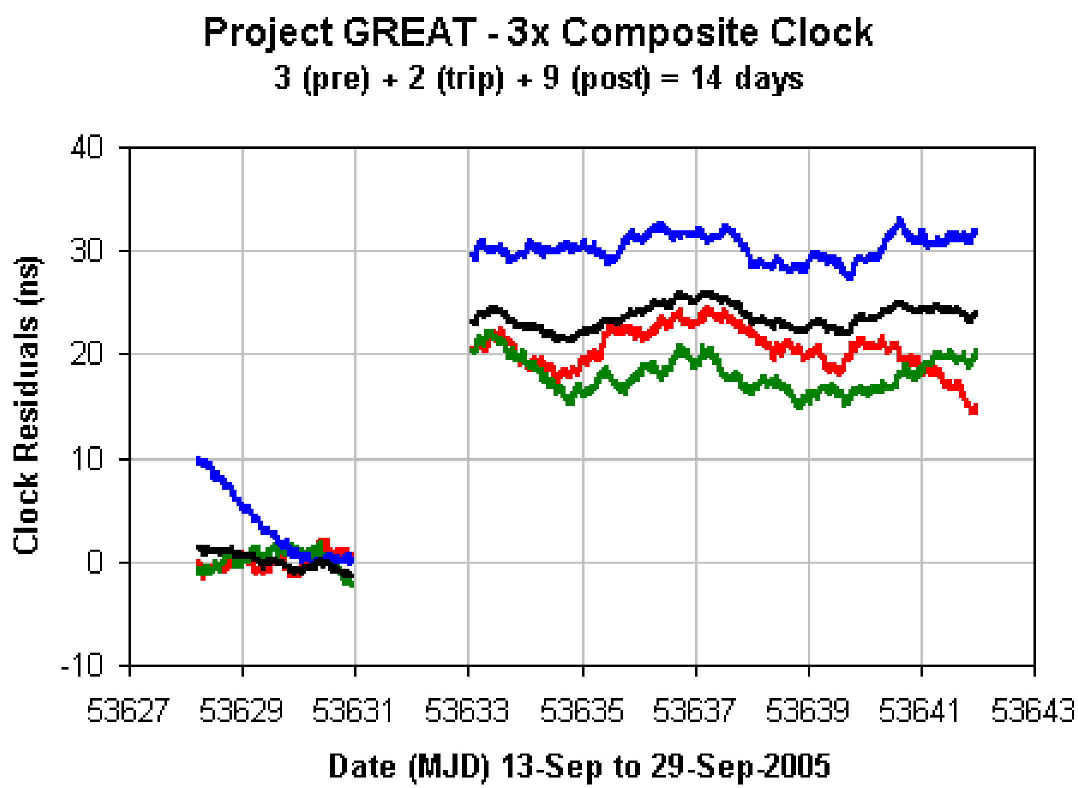
- 42 hours is up; time to leave. We’re all tired. Can this really work? Go home.

Time dilation: *prediction*

- Home clock and mountain clock elevations
- 5400 ft – 1000 ft = 4400 ft (1340 m)
- $\Delta f/f = 1.46\times10^{-13}$ times 42 hours = +22 ns

Time dilation: *measured*

- 3 clock mean
  23.2 ns
  ±4 ns
- Prediction
  22.4 ns
- Wow!



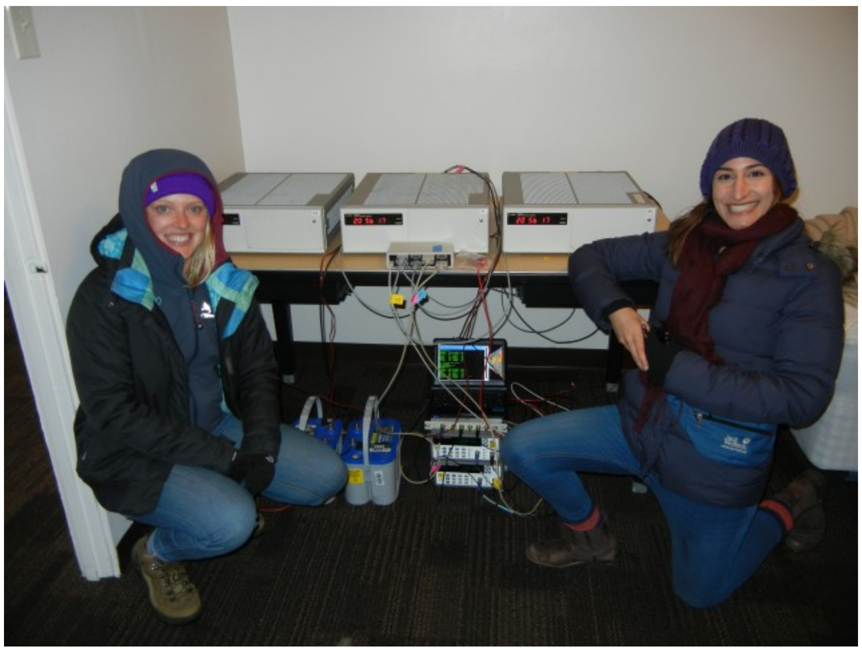
Project GRE²AT – summary

- Einstein was right; time dilation is real!
  - clocks (and we) came back 22 ns **older**
  - gravitational effect (elevation, *not* velocity)
  - unexpected press: WIRED, Physics Today, Reddit, Scientific American, even a physics textbook, etc.
- Now *”relativity is child’s play”*
- And then a decade later…

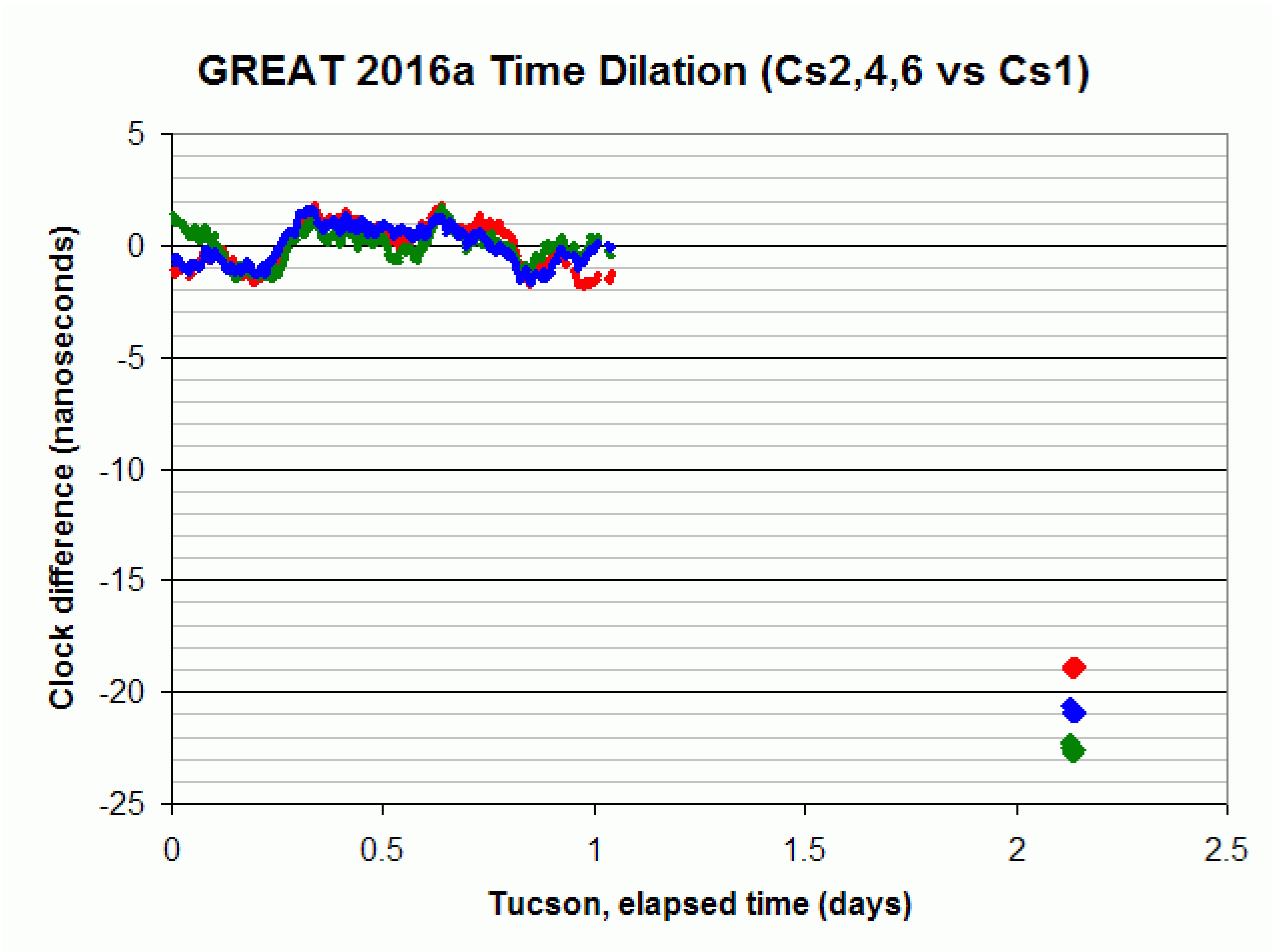
GREAT 2016a – Lemmon

- Stephen Hawking “GENIUS” series (PBS / BBC)
  - episode on space-time, clocks, time dilation
  - they asked me to repeat the GREAT experiment
- Mt Lemmon, Tucson, AZ (January 2016)
  - 9160 ft (2790 m) summit, dormitory
  - 2600 ft (790 m) base camp, hotel
  - UK film crew, tight schedule, no re-takes
- 2000 m × 24 hours = ~20 ns time dilation
  - used 3+3 cesium clocks


ITIME




2016a – time dilation results



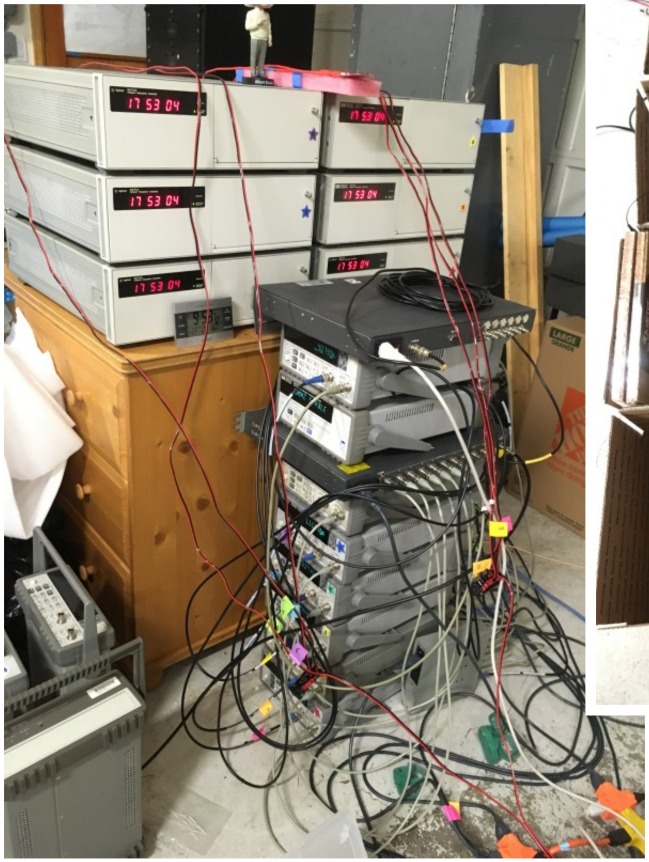
2016a – summary

- It worked! (much relieved)
  - up-down-up vs. down-up-down
  - different elevation and latitude (earth rotation)
- RIP Stephen Hawking (1942–2018)
- Show available on iTunes or *pbs.org*

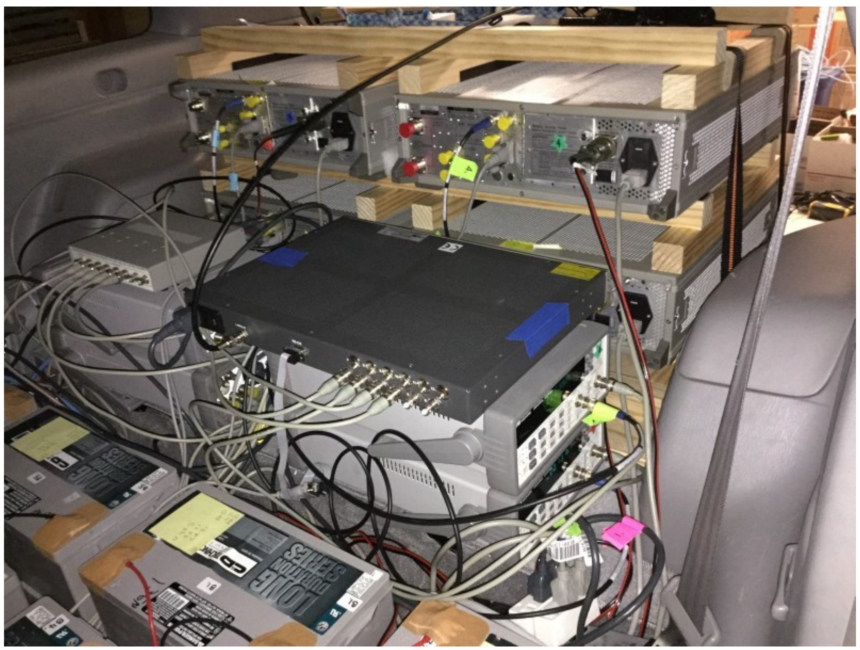
GREAT 2018a – Palomar

- Earlier this year (2018), another request
  - History channel, “In Search Of”, Zachary Quinto
- Demonstrate time dilation
  - sort of related to their “time travel” theme
- Palomar Mountain, CA
  - low clocks: Oceanside (sea level)
  - high clocks: Palomar Mountain (~5500 ft)
- Predicted time dilation: ~15 ns
  - used 2+2 cesium clocks

2018a – prep

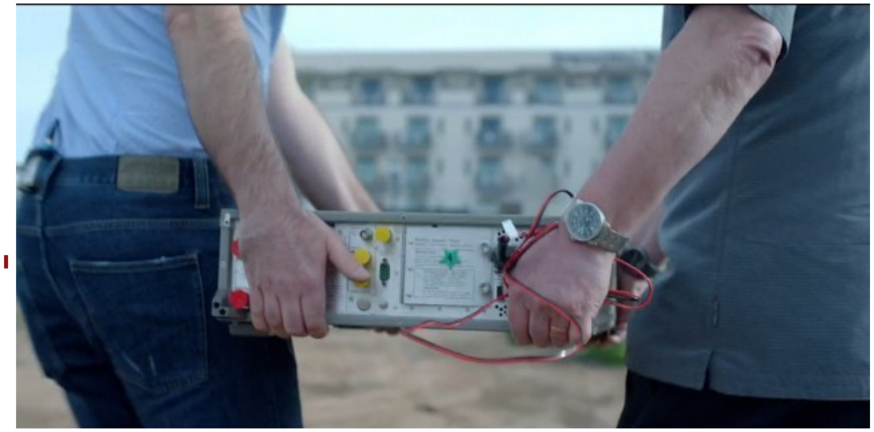


2018a – battery backup

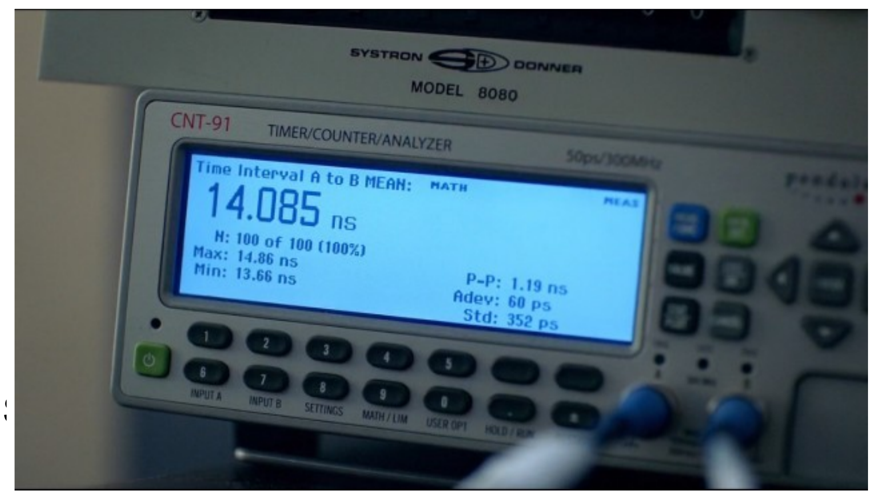



ELEVATION
5550 FT
SAN DIEGO
S6
COUNTY
END
CALIFORNIA INSTITUTE OF TECHNOLOGY
PALOMAR OBSERVATORY
VISITOR PARKING
ELEVATION
5550 FT.
HOURS
9 AM - 3 PM


BAILEY'S




ELEVATION
5000 FT


SYSTRON DONNER
MODEL 8080
CNT-91
TIMER/COUNTER/ANALYZER
Time Interval A to B MEAN: MATH
14.085 ns
N: 100 of 100 (100%)
Max: 14.86 ns
Min: 13.66 ns
P-P: 1.19 ns
Adev: 60 ps
Std: 352 ps
INPUT A
INPUT B
SETTINGS
MATH / LIM
USER OPT

2018a – summary

- Predicted time dilation: 15.5 ns
  - based on recorded elevation and dwell time
- Measured time dilation: 14.1 ns
  - another success!
  - Cs1 to Cs4: 14.3 ns
  - Cs3 to Cs5: 13.8 ns
- Show available on iTunes or *history.org*

Conclusion

- Welcome to the world of amateur precise time
  - fascination with time, vintage and atomic clocks, counters, experiments, GPS, relativity, etc.
- GR time dilation experiments
  - just for fun, with the kids, and
  - larger audience via talks, TV episode or two
- Looking for interesting new venues
  - below sea level, or deep underground?
  - 50th anniversary of Hafele-Keating in 2021

Thanks

- Thanks to Tom Langenstein, Leo Hollberg, and Ralph Devoe (via *time-nuts*).
- Thanks for your time…

- Contact: tvb@LeapSecond.com
- Website: www.LeapSecond.com

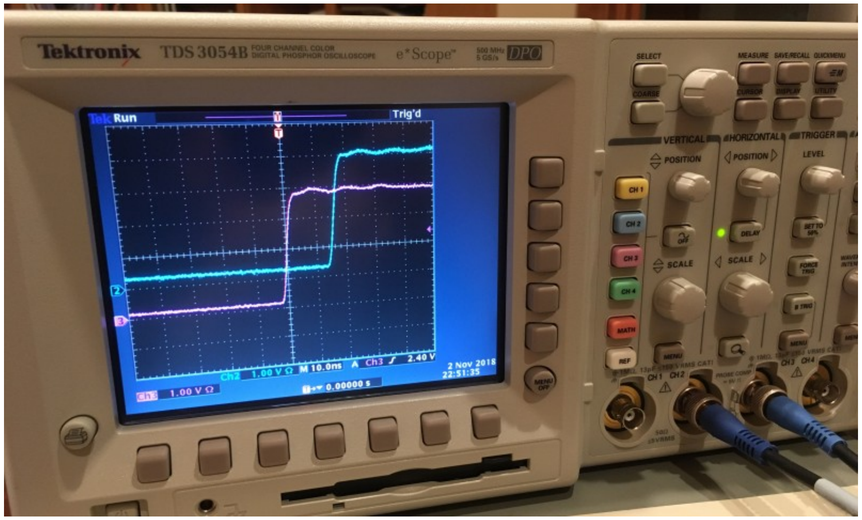
- Questions?

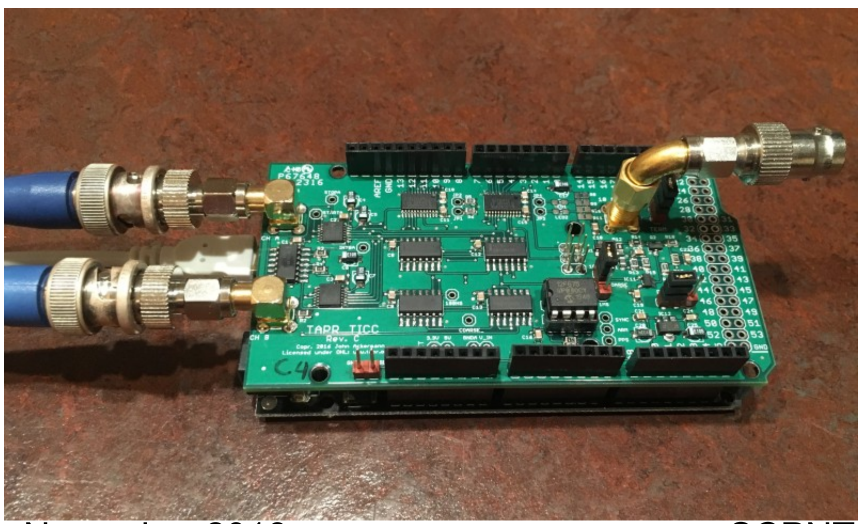
Backup slides

Time interval counter (TIC)

- Time-To-Digital
  - start input
  - stop input
- Trigger
  - pos/neg slope
  - AC/DC input
  - trigger level
- Resolution

Comparing clocks / nanosecond





Terrestrial relativity math, easy

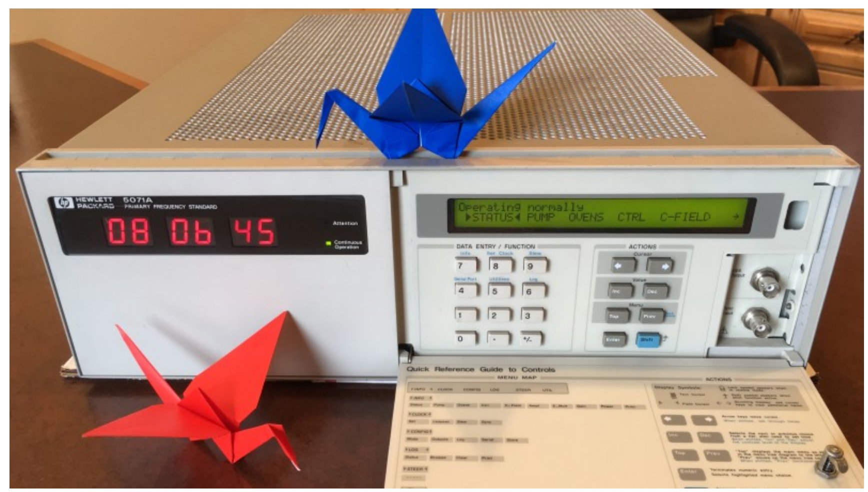
- At modest speeds and modest elevation
  - time dilation equations become very simple
- Kinematic effect (moving clocks run slower)

  $\Delta f/f \approx -\frac{1}{2}v^2/c^2$
- Gravitational effect (lower clocks run slower)

  $\Delta f/f \approx +gh/c^2$
- Sign? SI second defined at sea level
  - so clocks speed up with higher altitude
  - “speed up” is actually “slow down less”

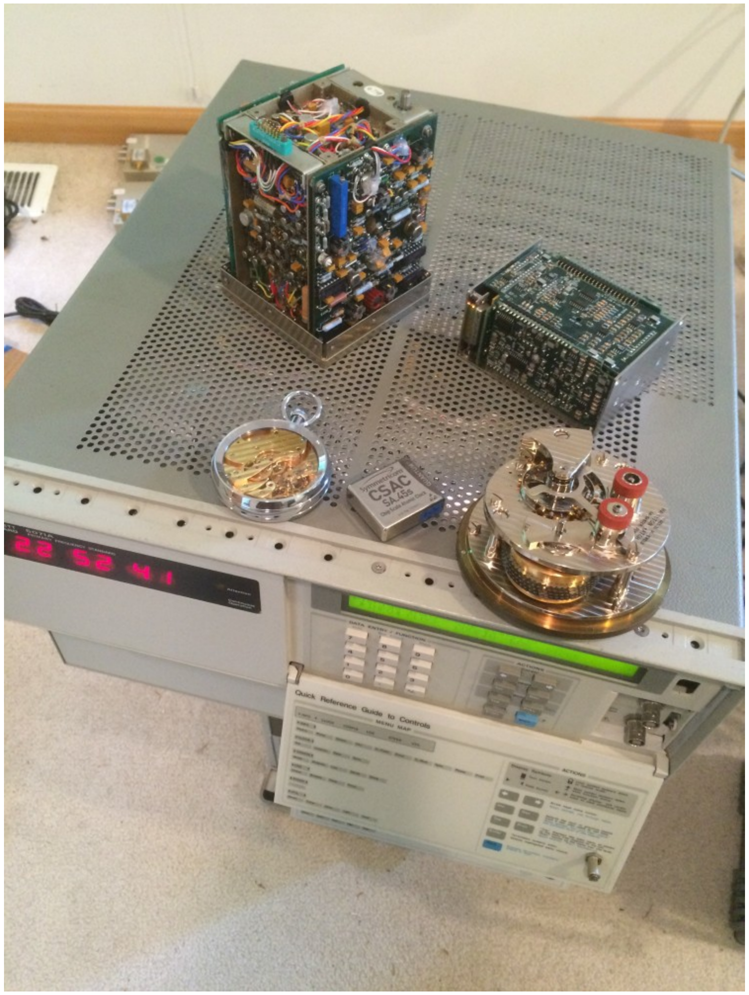
Power of c^2

- Speed of light
  $c \approx 300\,000\,000$
  $c^2 \approx 90\,000\,000\,000\,000\,000$
  $1/c^2 \approx 0.000\,000\,000\,000\,000\,01$
- $E = mc^2$
  - c^2 in numerator
  - very, very large
- $\Delta f/f = gh/c^2$
  - c^2 in denominator
  - very, very small
- As they say:
  "make time dilation, not war"



First “atomic” wristwatch

Smaller and smaller … CSAC



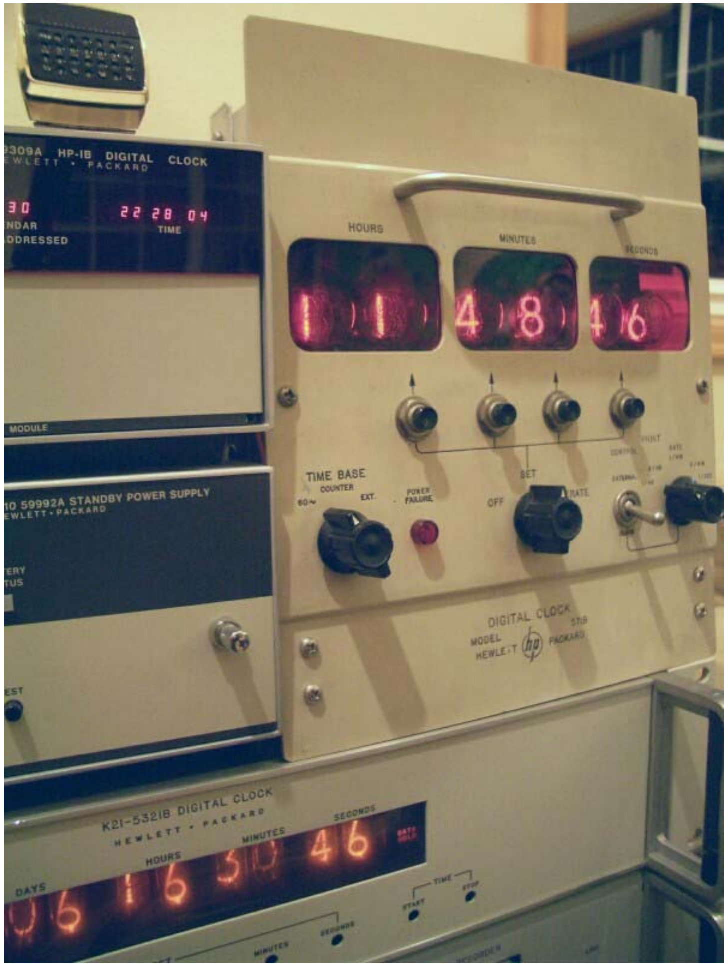
Museum of *hp* clocks

HP quartz

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

HP clocks

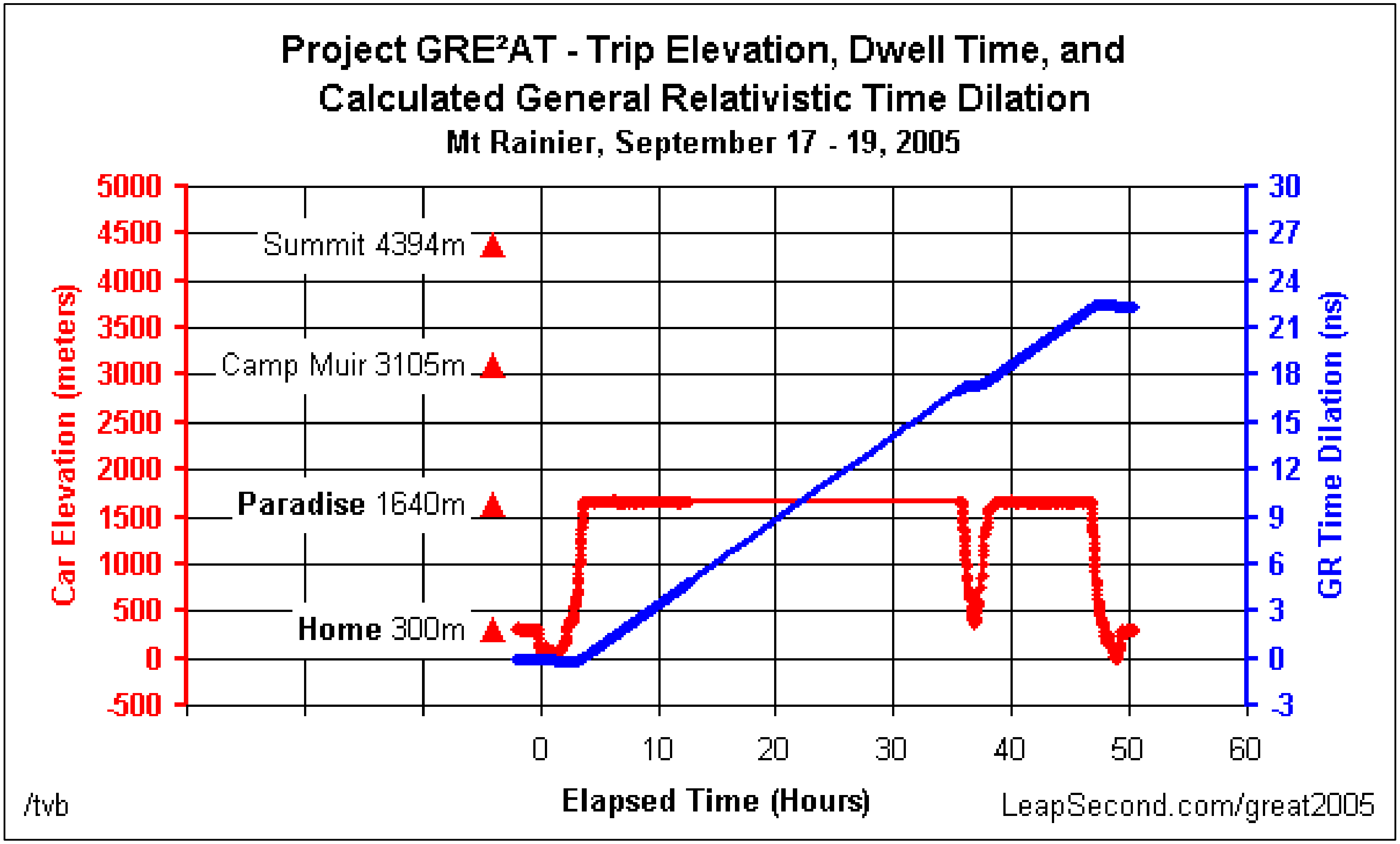
- HP01
- 571B
- 5321
- 117A
- 114BR
- 115BR
- 113AR



HP cesium & rubidium

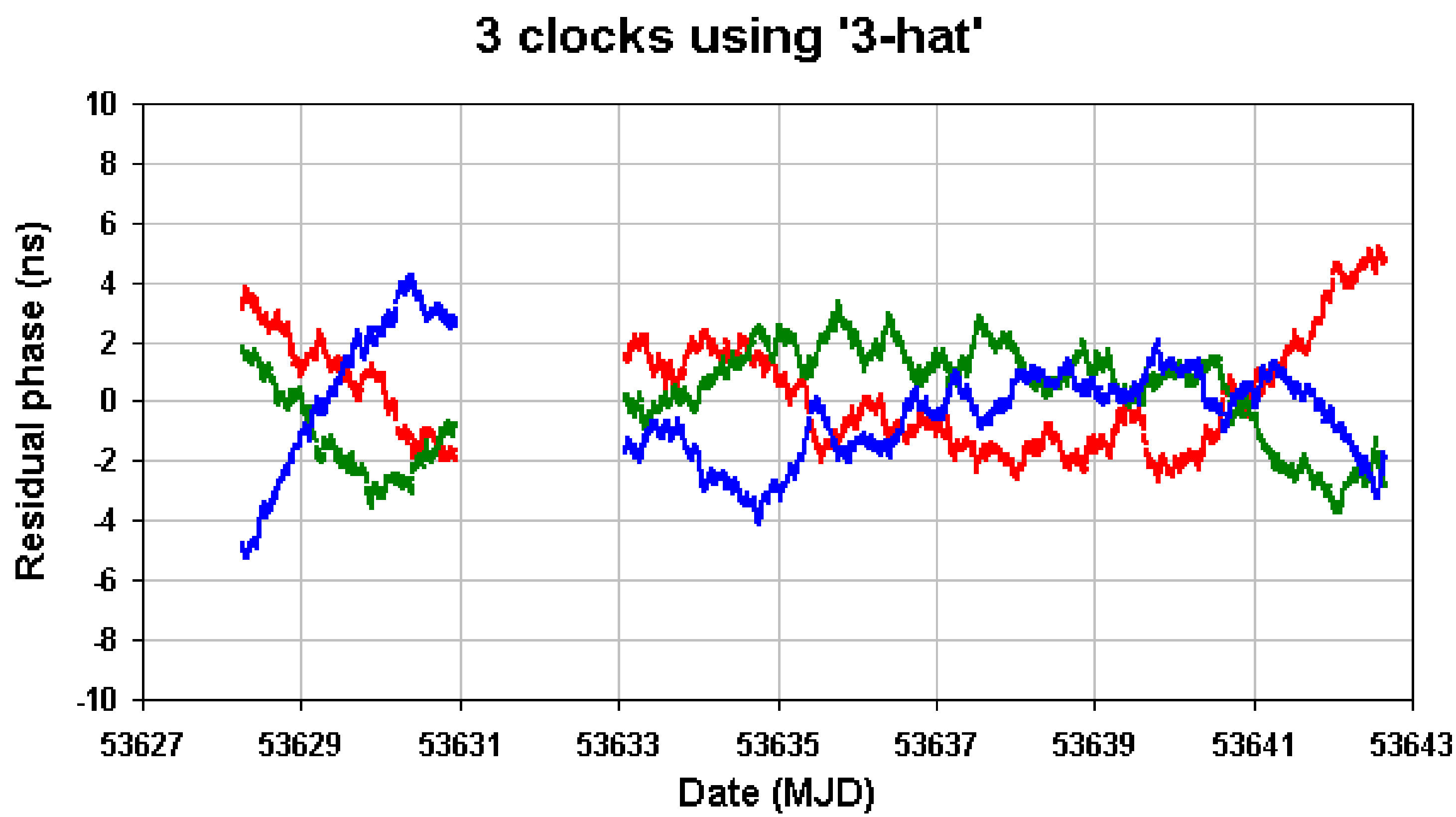
- 5071A
- 5065A
- 5062c
- 5061B
- 5061A
- 5060A

Elevation and *predicted* dilation



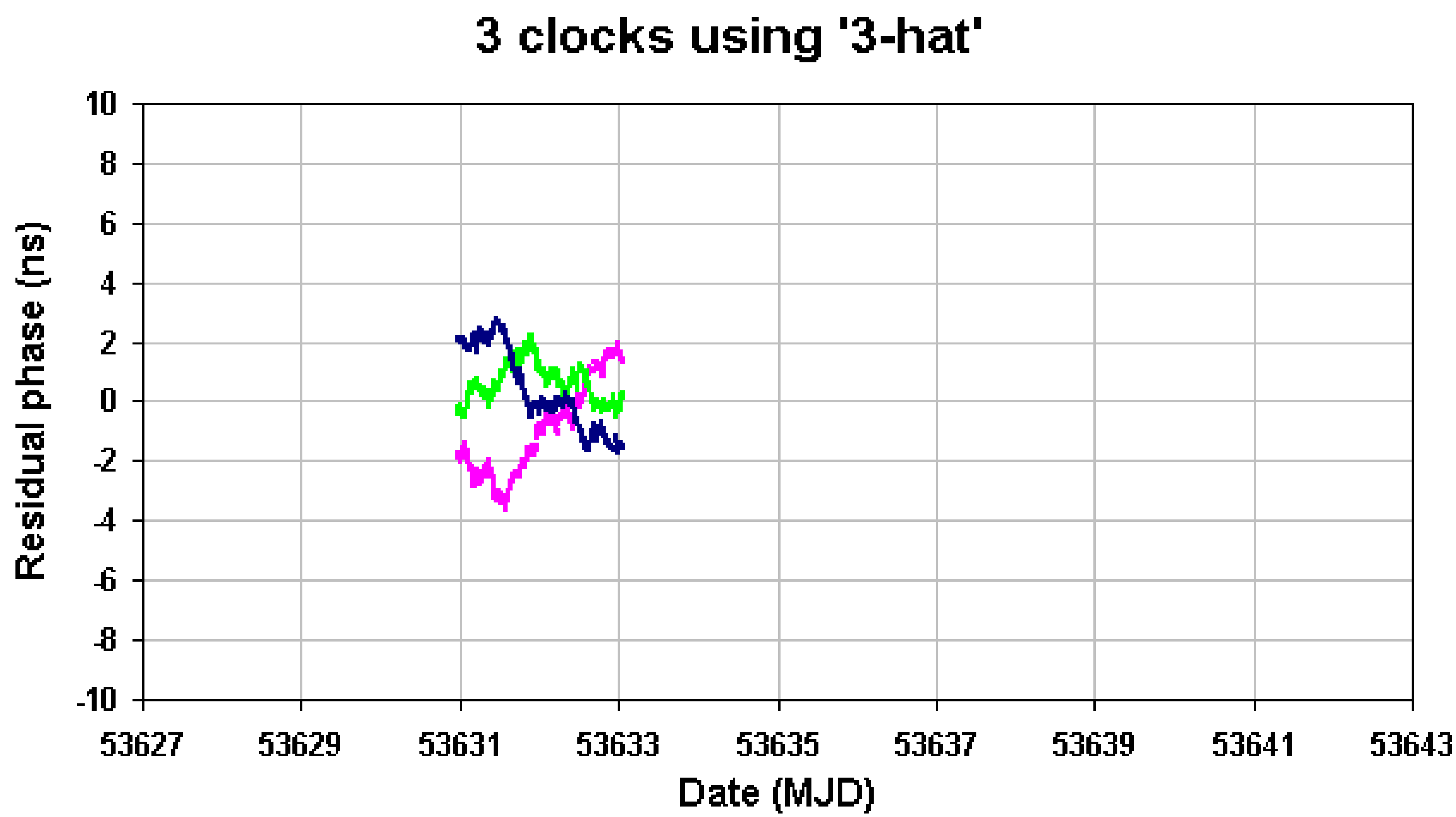
3-hat, residuals (home)

- $Cs_i – Cs_j$ via lab reference



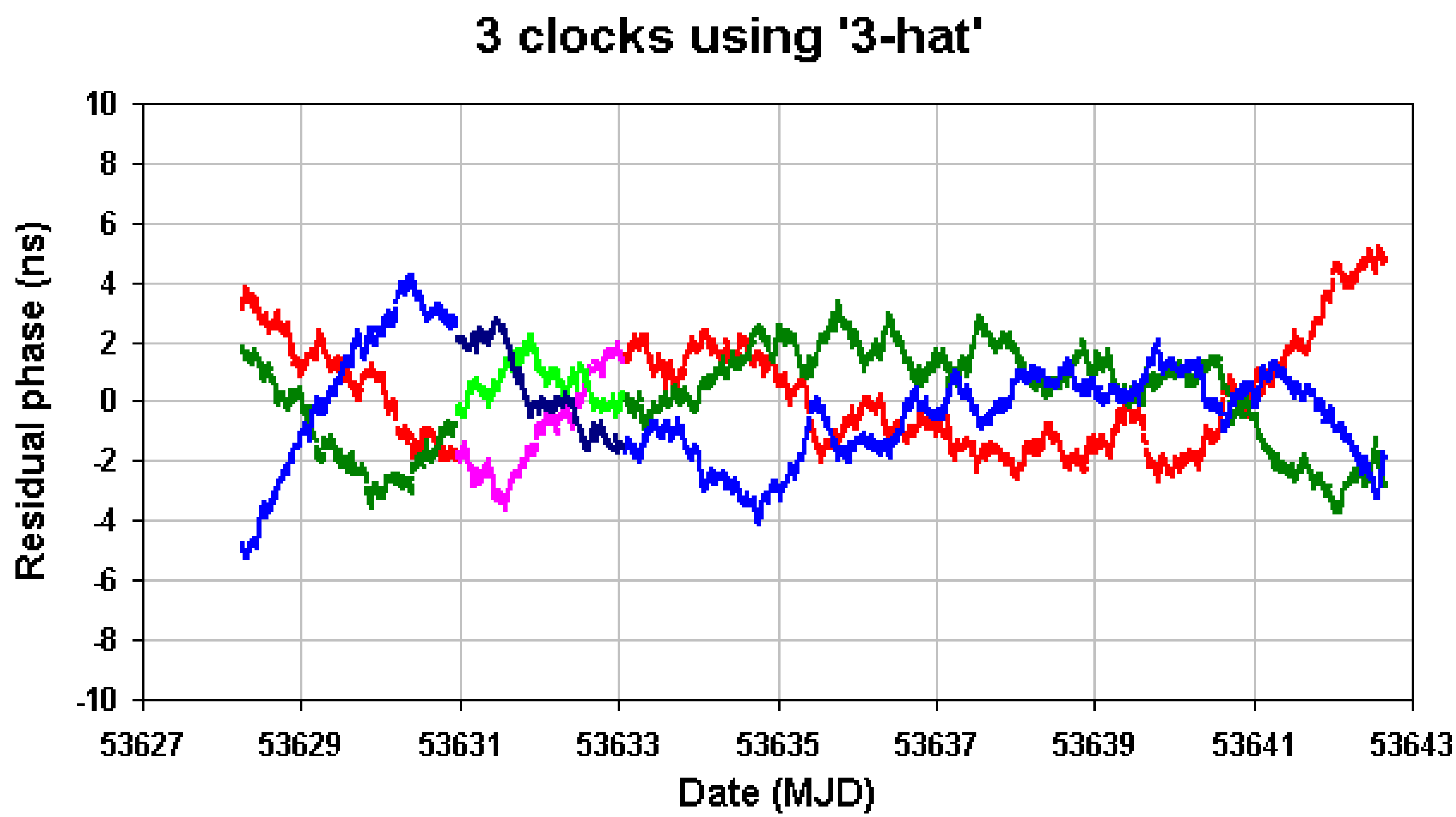
3-hat, residuals (away)

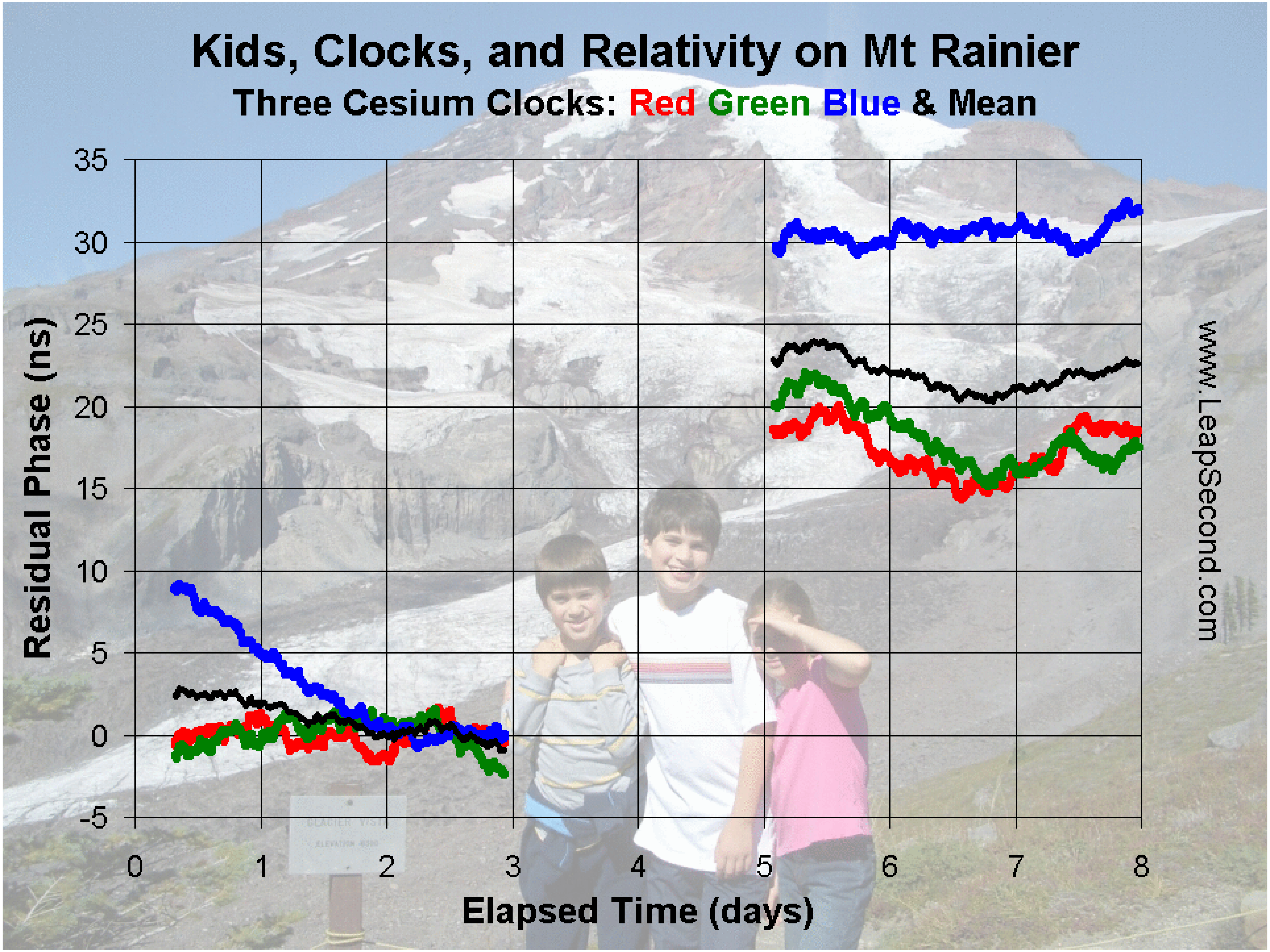
- $Cs_i - Cs_j$ via mutual-comparisons



3-hat, residuals (combined)

- $Cs_i - Cs_j$



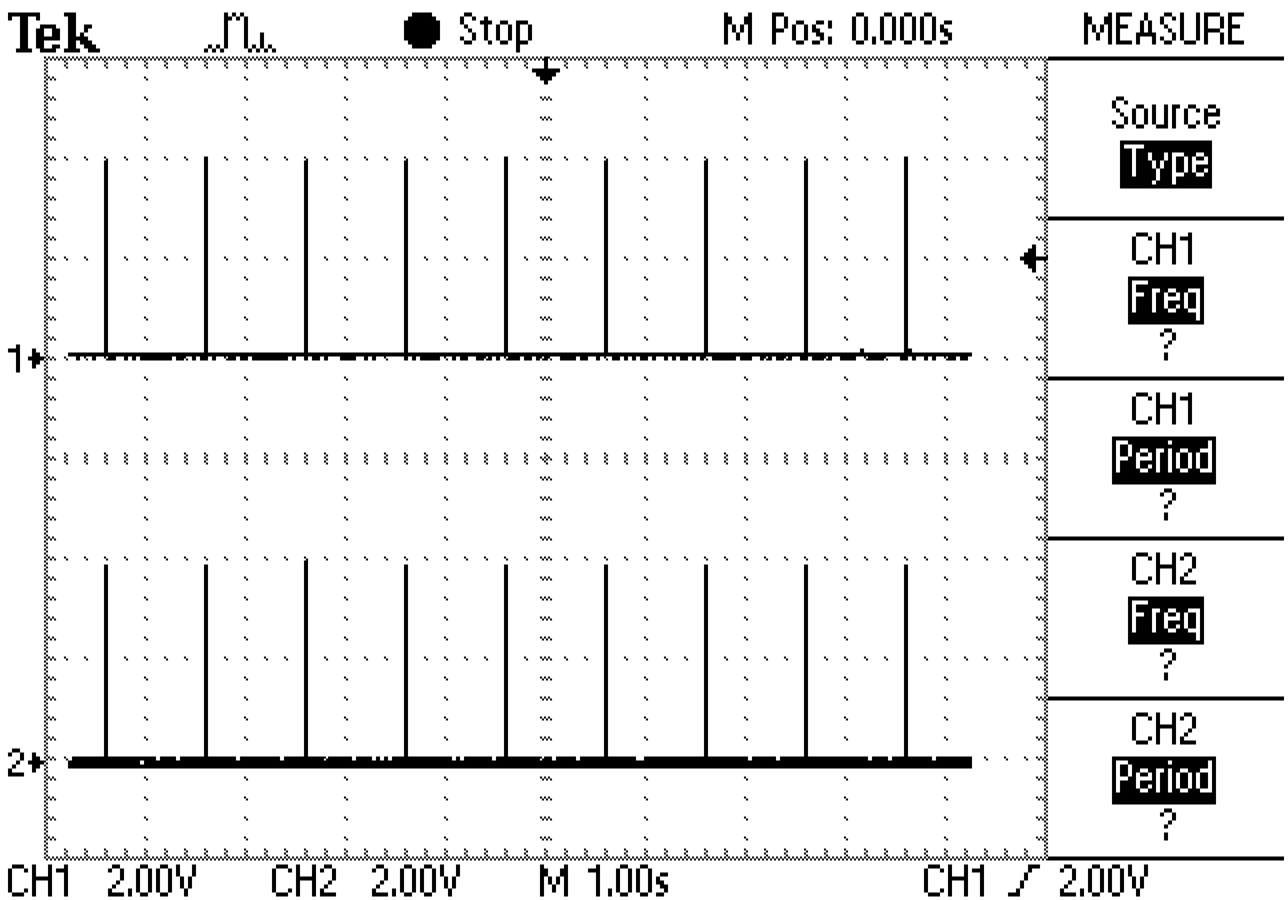


Kids, Clocks, and Relativity on Mt Rainier
Three Cesium Clocks: Red Green Blue & Mean
Residual Phase (ns)
35
30
25
20
15
10
5
0
-5
0
1
2
3
4
5
6
7
8
Elapsed Time (days)
www.LeapSecond.com

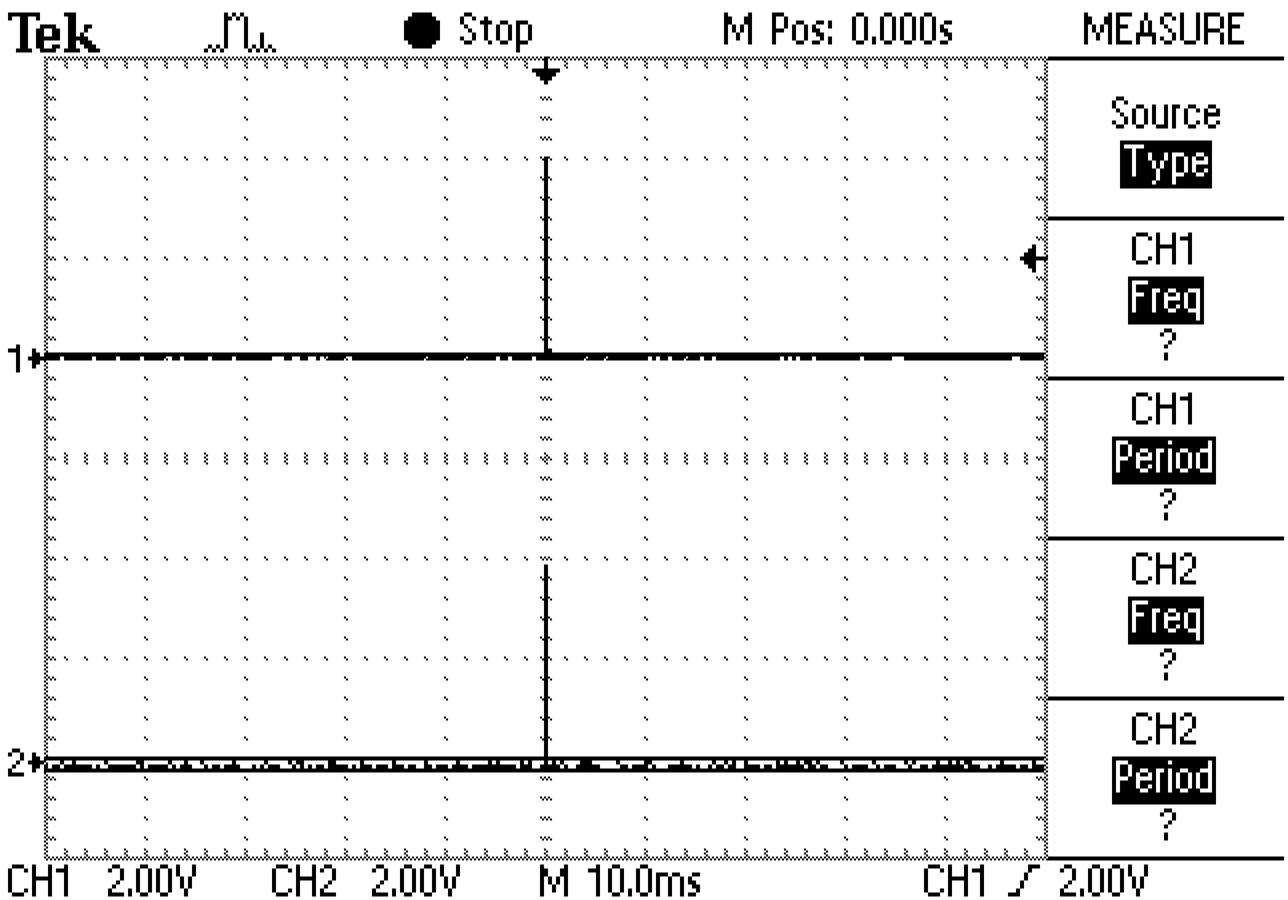
Chronometer adjust (time, rate)

Frequency adjust

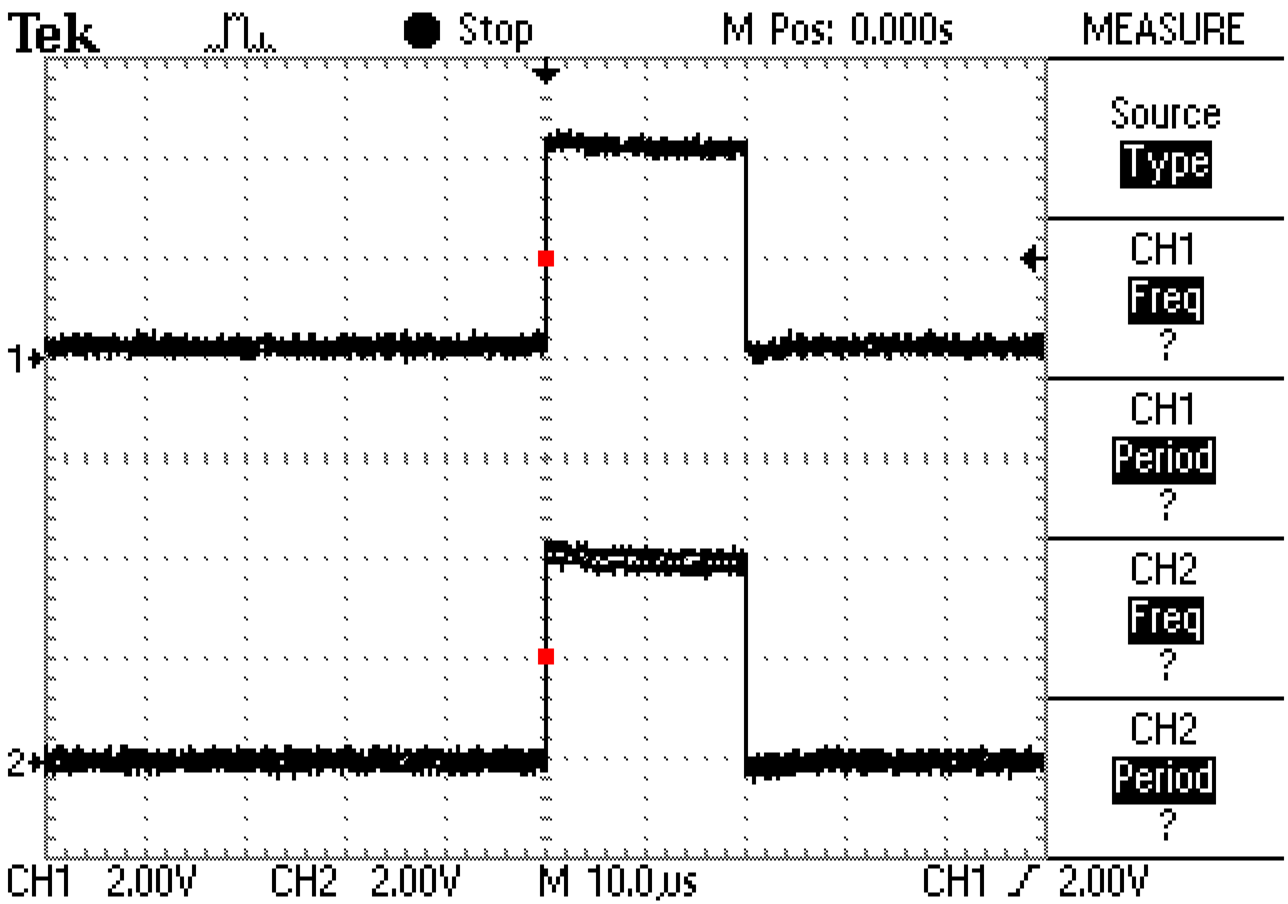
Atomic clock 1PPS – 10 s



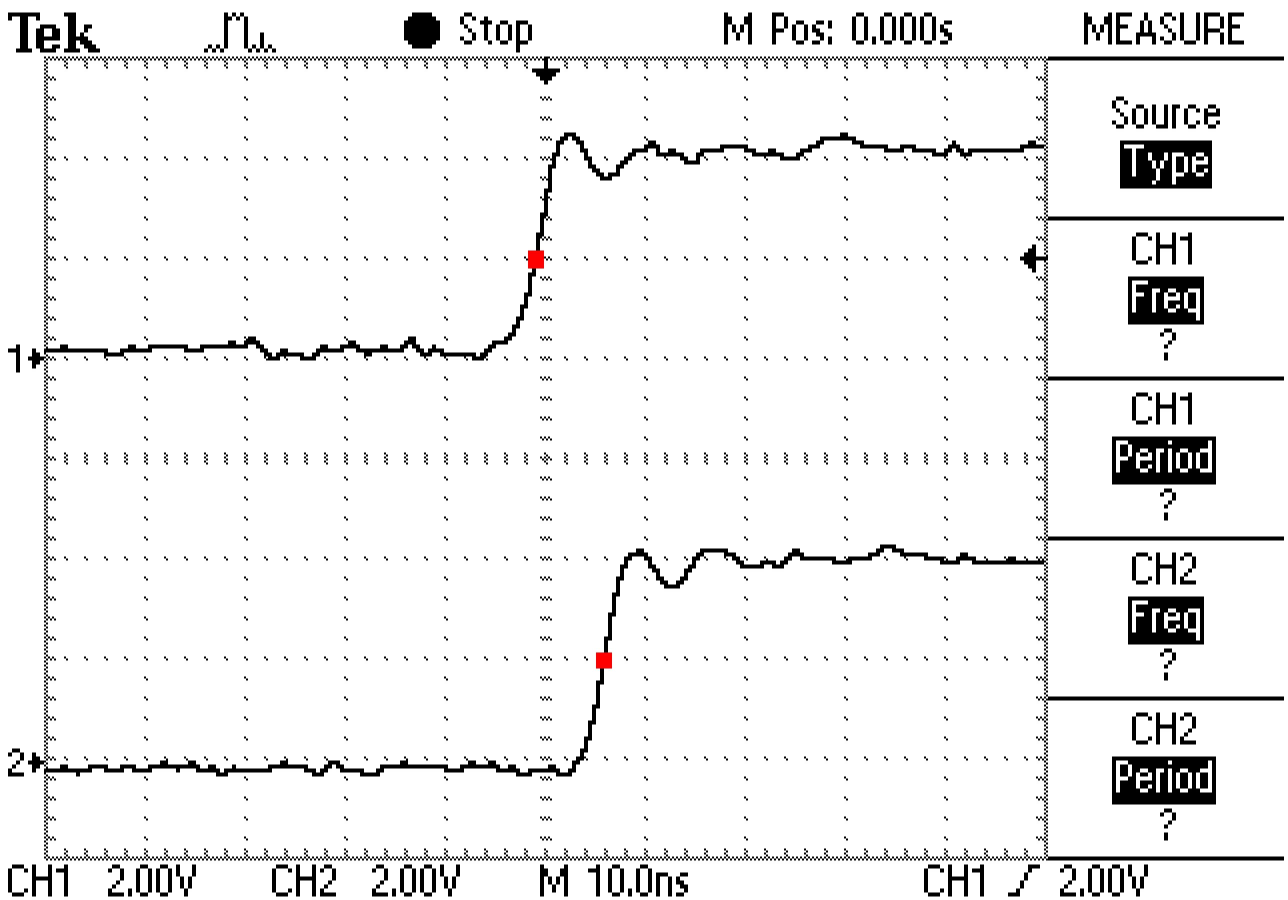
Atomic clock 1PPS – 10 ms/div



Atomic clock 1PPS – 10 μs/div



Atomic clock 1PPS – 10 ns/div



Cesium 9,192,631,770 Hz