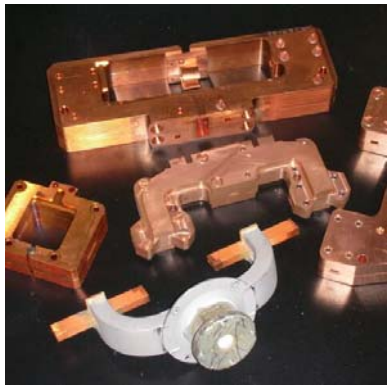
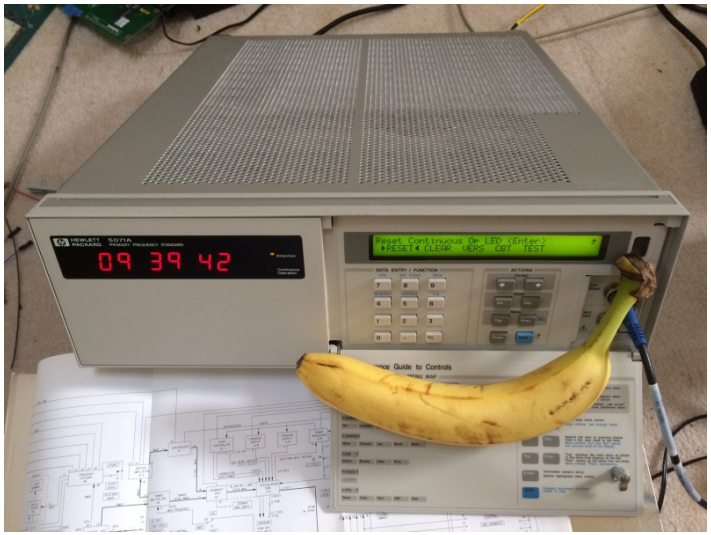


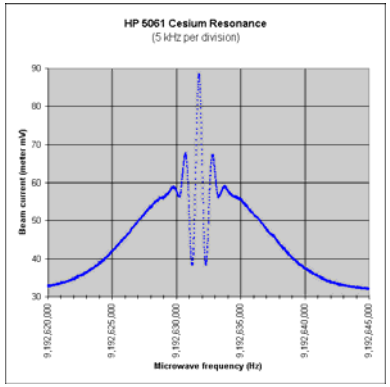




Atomic Timekeeping as a Hobby

Tom Van Baak (tvb)

www.LeapSecond.com



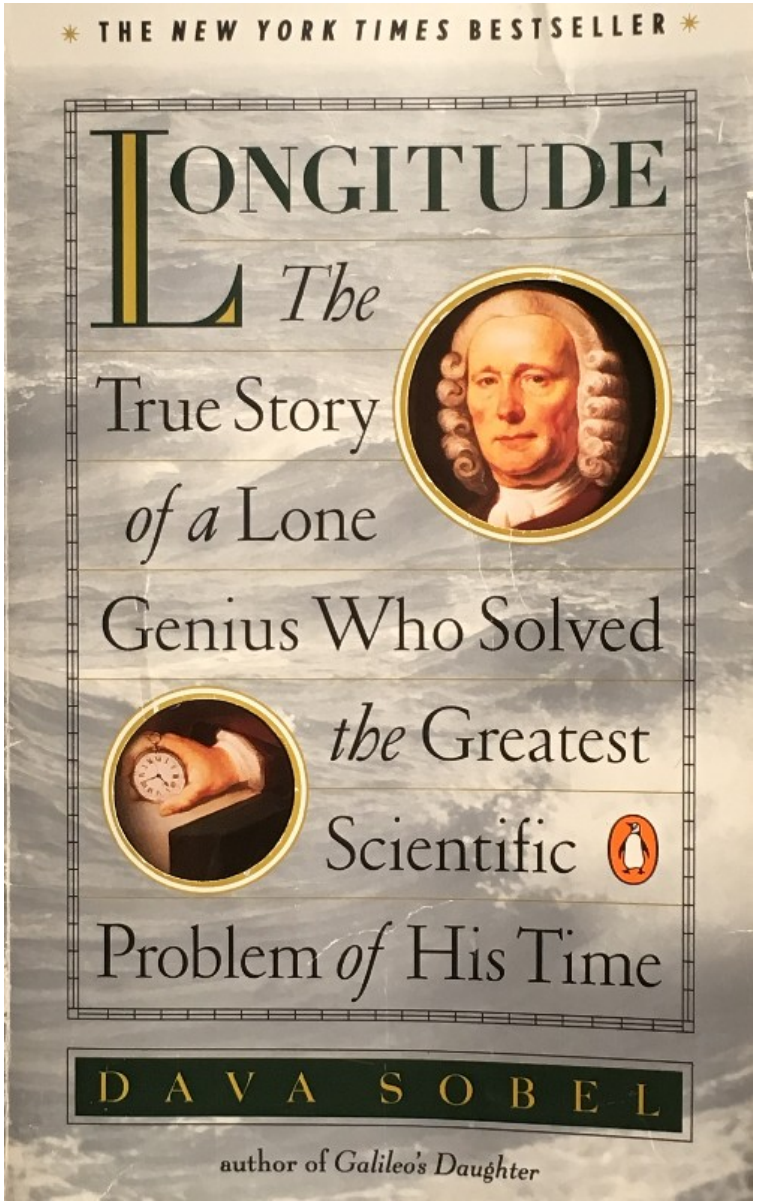


Outline

- Part 1 – Navigation and traveling clocks
  - clocks, timing, the ‘T’ in PNT
- Part 2 – Atomic clock collecting hobby
  - going to extremes at home
- Part 3 – *LeapSecond.com* and *time-nuts*
  - sharing the hobby with thousands
- Part 4 – Project GREAT
  - DIY gravitational time dilation experiment(s)

Chronometers at sea

- Who is this?
  - John Harrison
- See all the clocks?
  - H1, H2, H3, H4 sea clocks
  - genius clockmaker
  - visit Greenwich; still running!
- "Longitude prize" winner
  - 1759 (250+ years ago)
  - ***he put the "T" in PNT***
- Read.the.book
  - by Dava Sobel

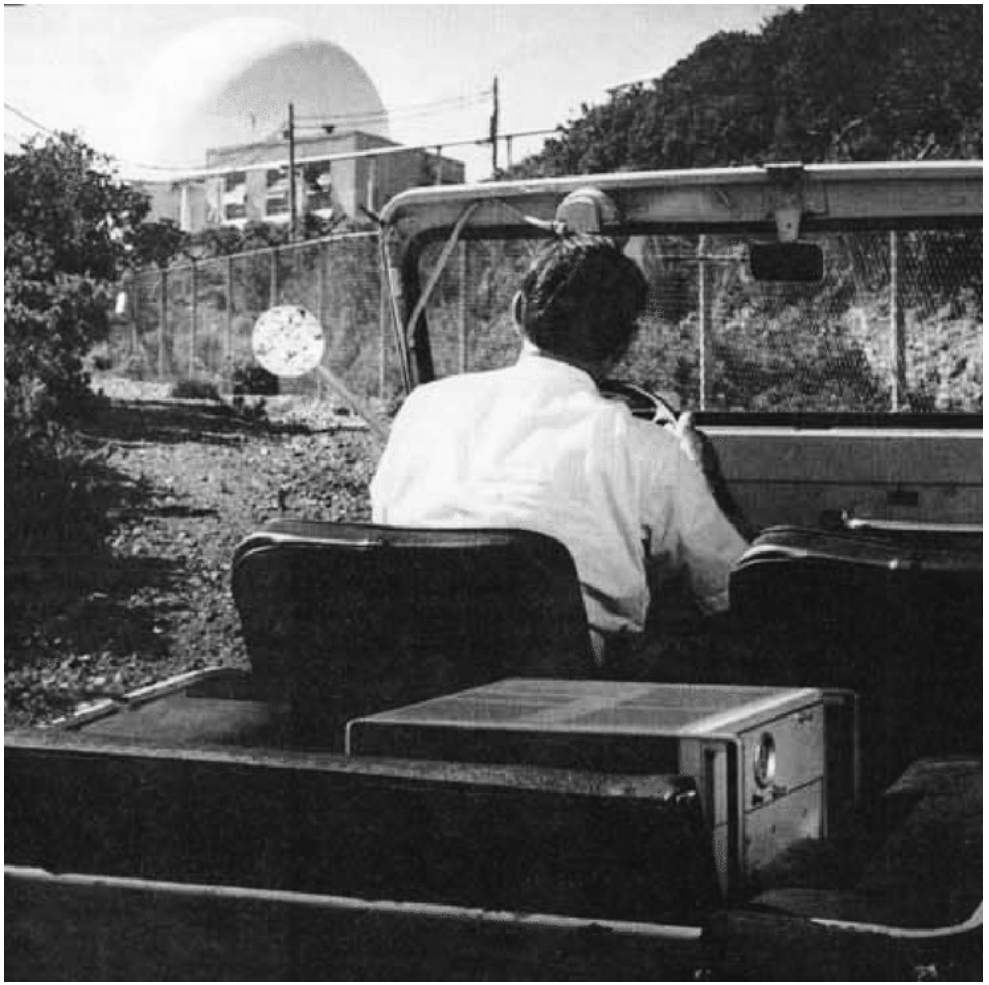


Cesium “chronometers” by air

- Who is this?
  - Len Cutler, *hp* clockmaker
- See the clock?
  - model *hp* 5060A
  - cesium beam atomic standard
  - batteries & divider/clock
- Mission?
  - time synchronization
  - cross-country
  - round-the-world
  - 1960’s “flying clock” era
  - Military, NASA, Apollo
  - Harrison + 200 years

Cesium “chronometers” by land

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



Flying clocks around-the-world

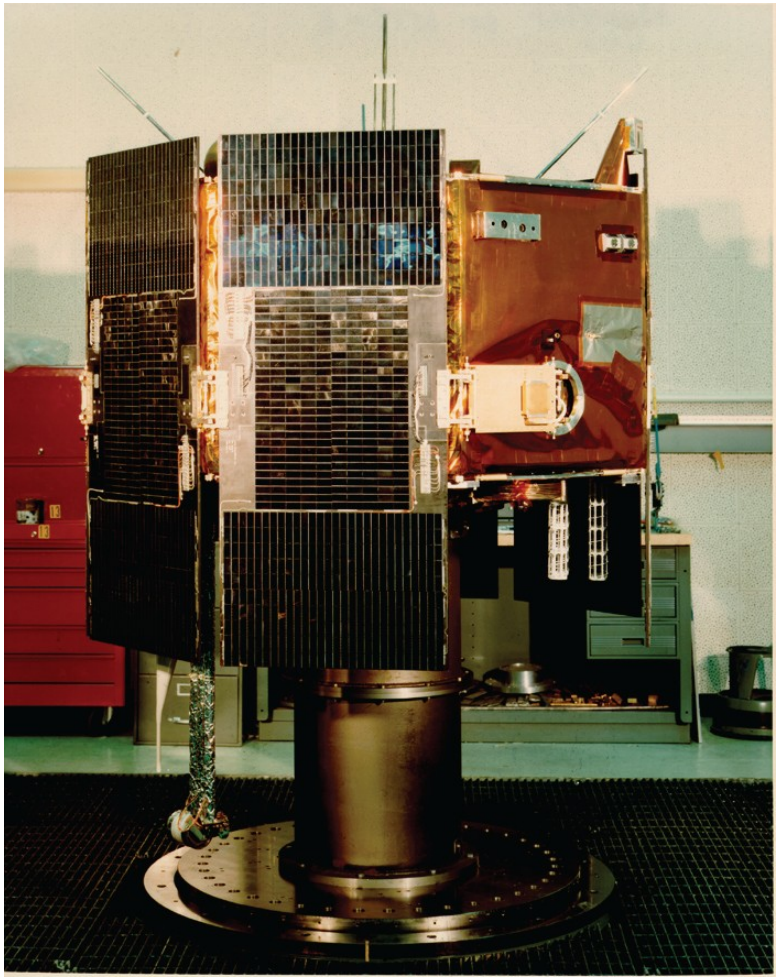
- Who is this?
  - J.Hafele & R.Keating
- See all the clocks?
  - 4 @ *hp* 5061A
  - AC/DC power backups
  - time interval counter
- Relativity experiment
  - year 1971
  - commercial flights
  - RTW, twice! (6 days)
  - positive results

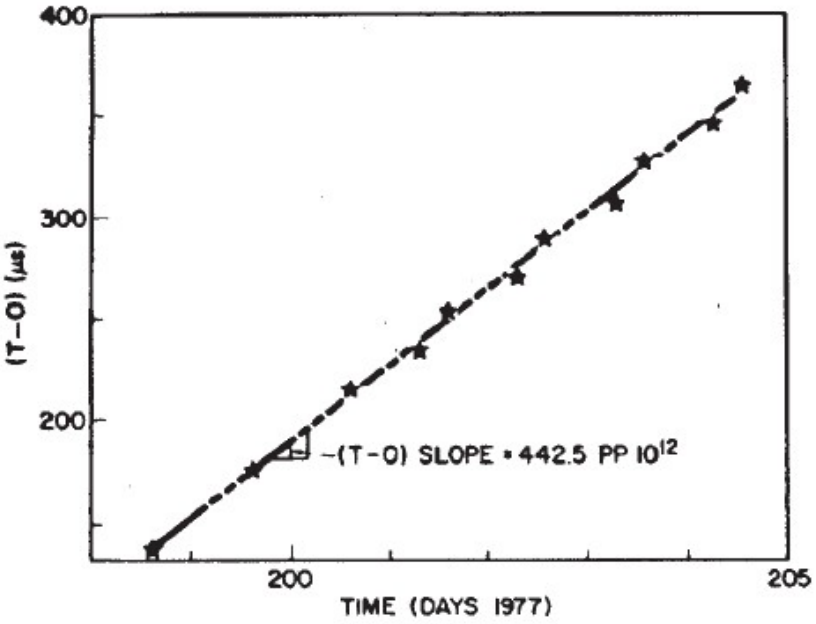
Space test: GP-A

- Ultimate “flying” clocks: spacecraft
- Gravity Probe A
- 1976, first *H-maser* in space
  - Robert Vessot, clockmaker
  - Martin Levine, clockmaker
- Successful test of relativity
  - science mission
  - launched to 10,000 km
  - 2 hour flight up / down
  - 60 ppm accuracy

Orbital test: Timation / NTS-1 / NTS-2

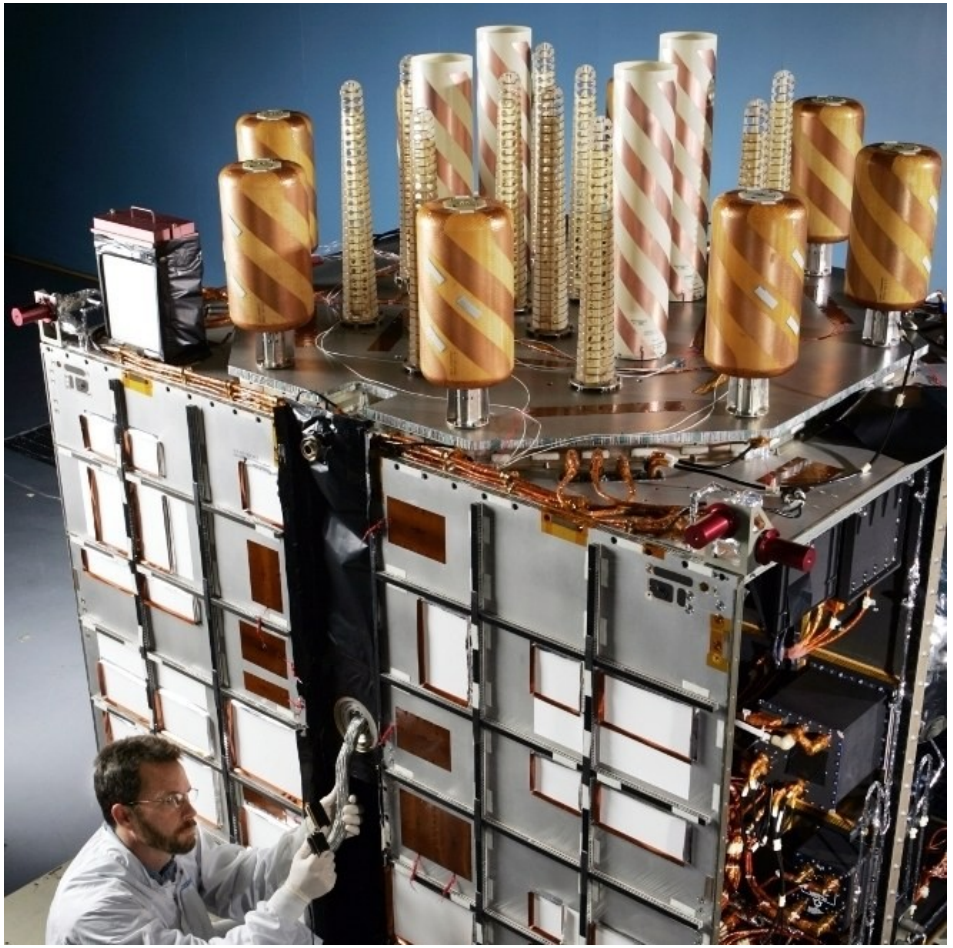
- Navigation Technology Satellite
- 1974, NTS-1, *rubidium* clock(s)
  - Efratom, clockmakers
- 1977, NTS-2, *cesium* clock(s)
  - FTS, clockmakers
- Test of GPS relativistic effects





32 atomic clocks in space: GPS

- What's this?
  - GPS IIR-M
- 250 year evolution from
  - Harrison to GPS
  - seconds/day to ns/day
  - 1 clock, to 32, to 100+
- Harrison would be happy
  - that we still use precise clocks for navigation,
  - that we use precise clocks for so much more …



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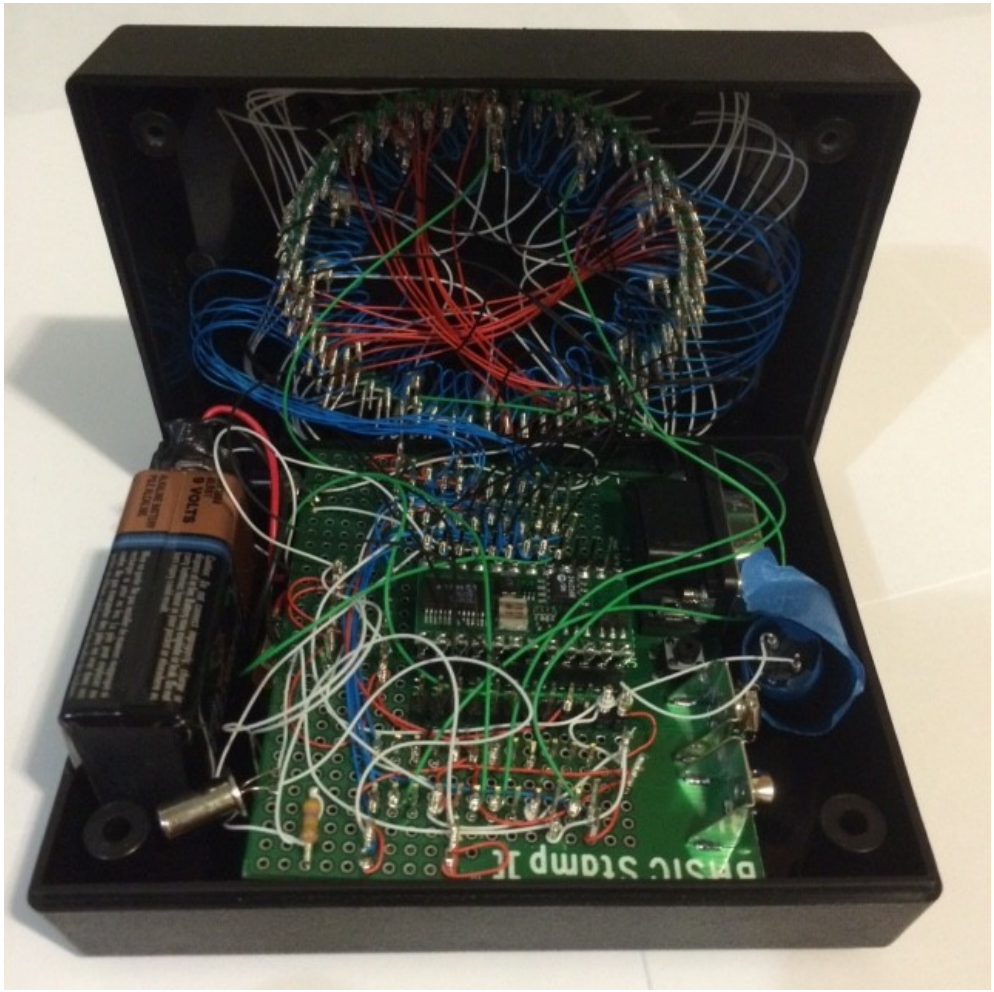
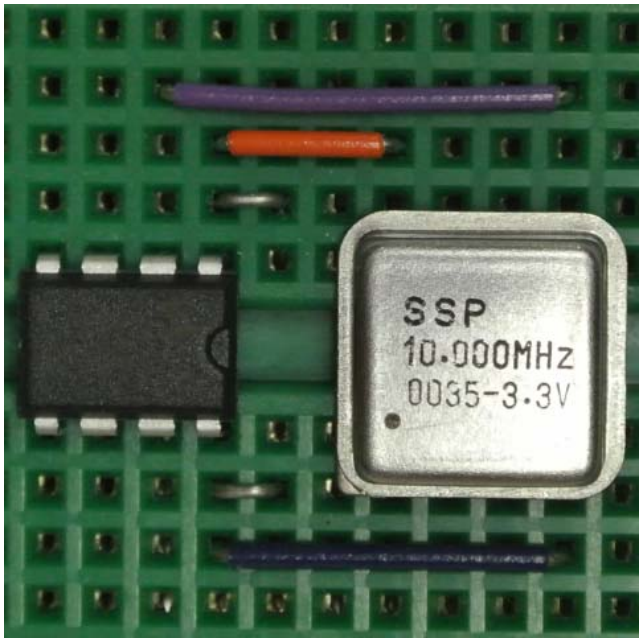
Precise time as a hobby

- DIY portable analog / digital microprocessor LED clock



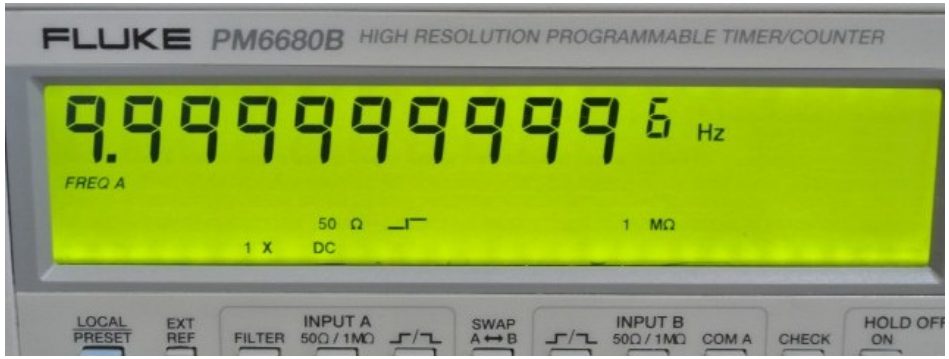
How can it keep good time?

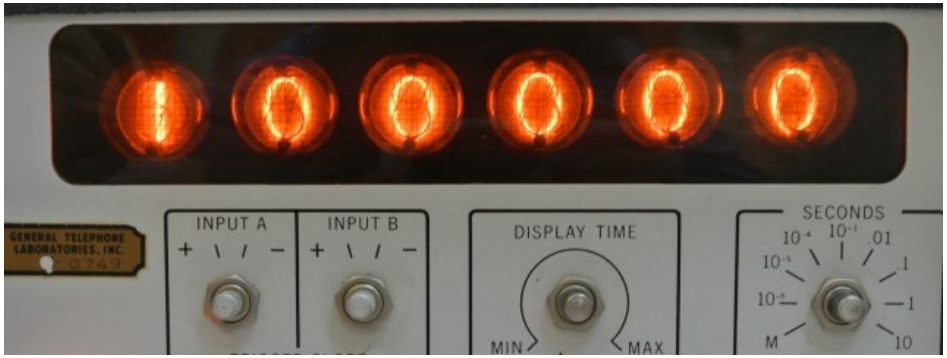
- It's the "timebase", here a 10 MHz quartz oscillator
  - How accurate is it? How to measure it?
- Use a "frequency counter"
  - 0.01 / 10.00 MHz = 0.1% (90 sec/day)
  - 0.0001 / 10 MHz = 10 ppm (1 sec/day)
  - But, how accurate is it? How to measure it?

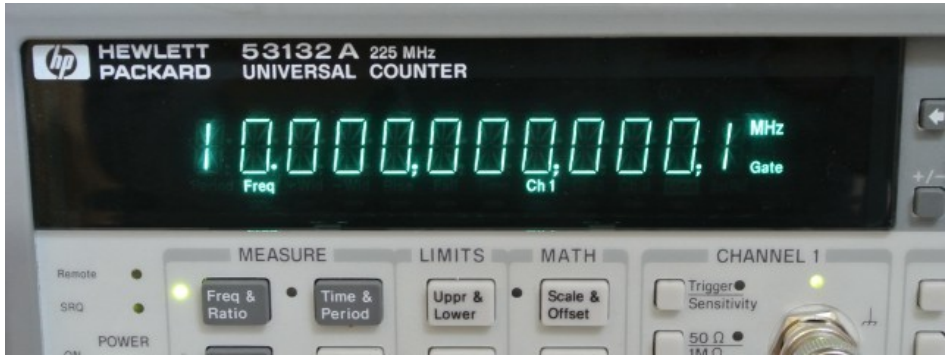


The quest for better oscillators…

The quest for more digits…



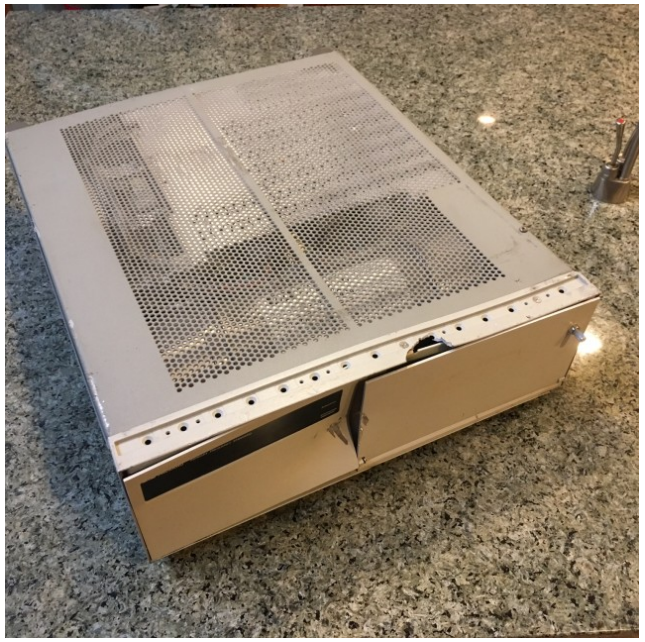


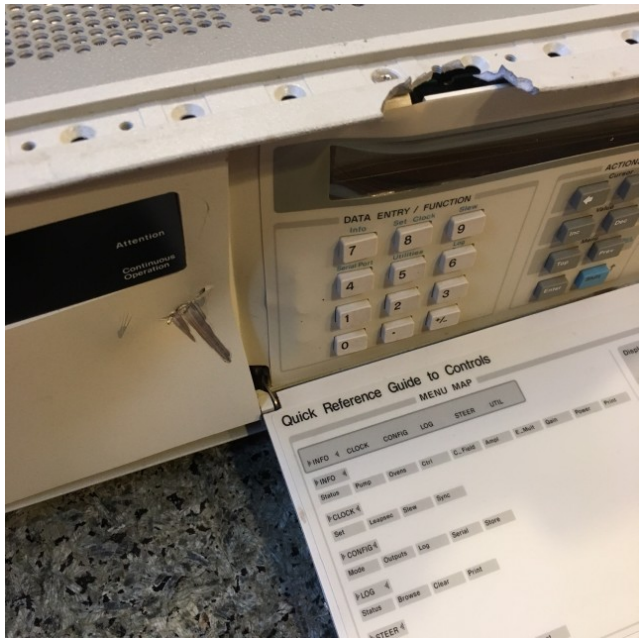


The quest for larger time lab…

Vintage *hp* 5061A cesium clock (eBay)

Surplus *hp* 5071A cesium clock (eBay)

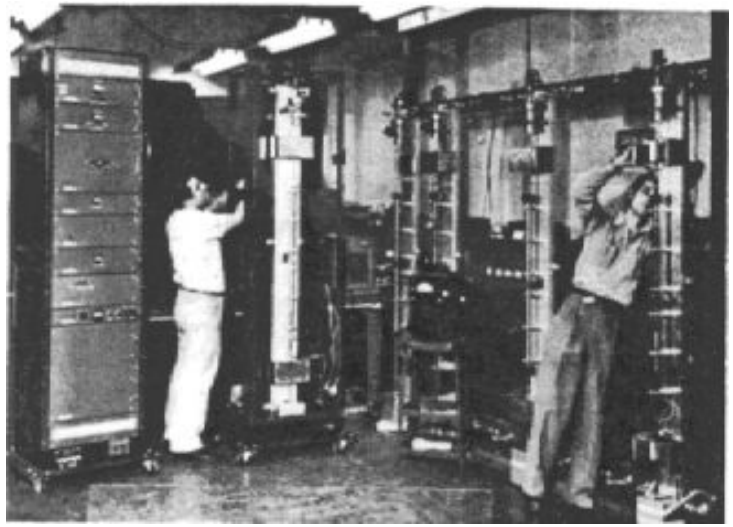


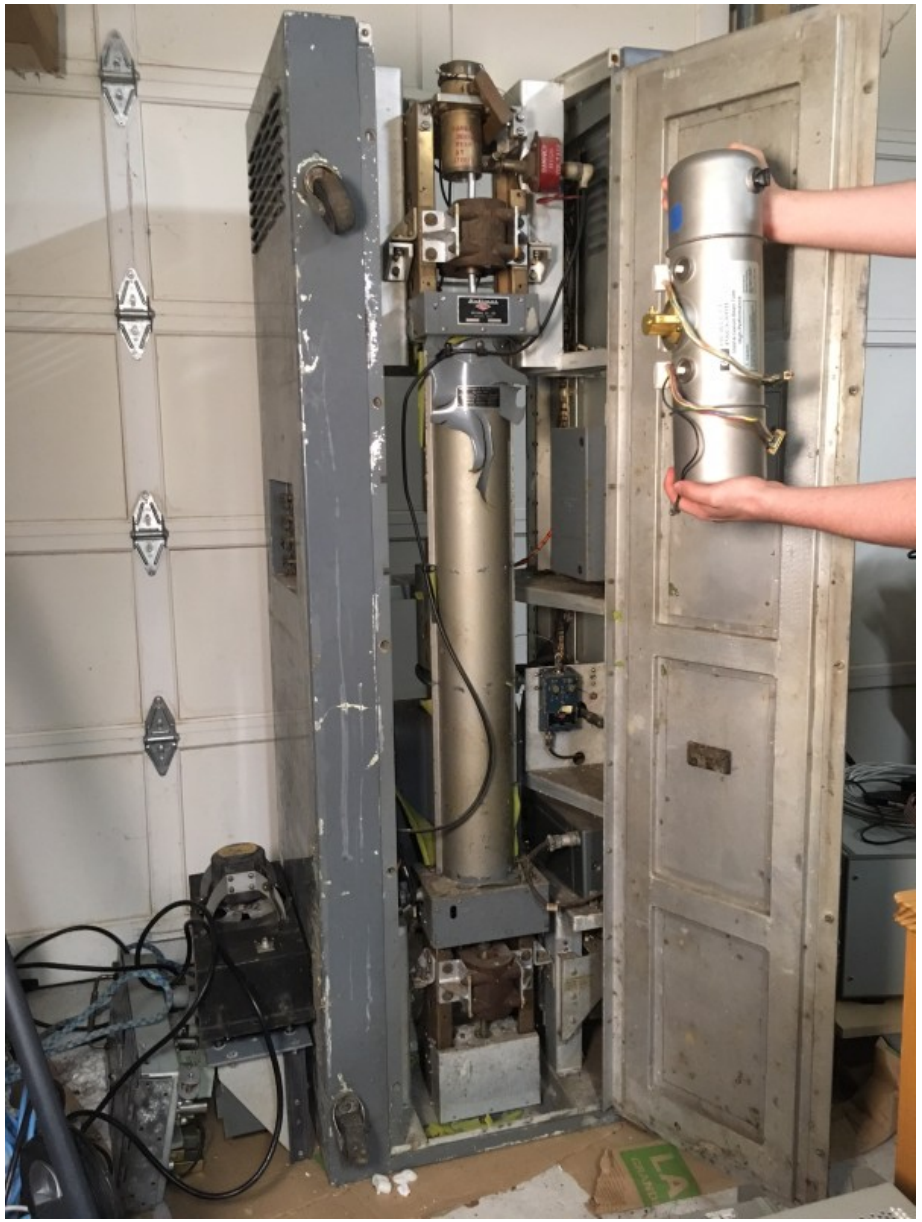


Museum of *hp* clocks

Rare NC-2001 Atomichron (eBay)

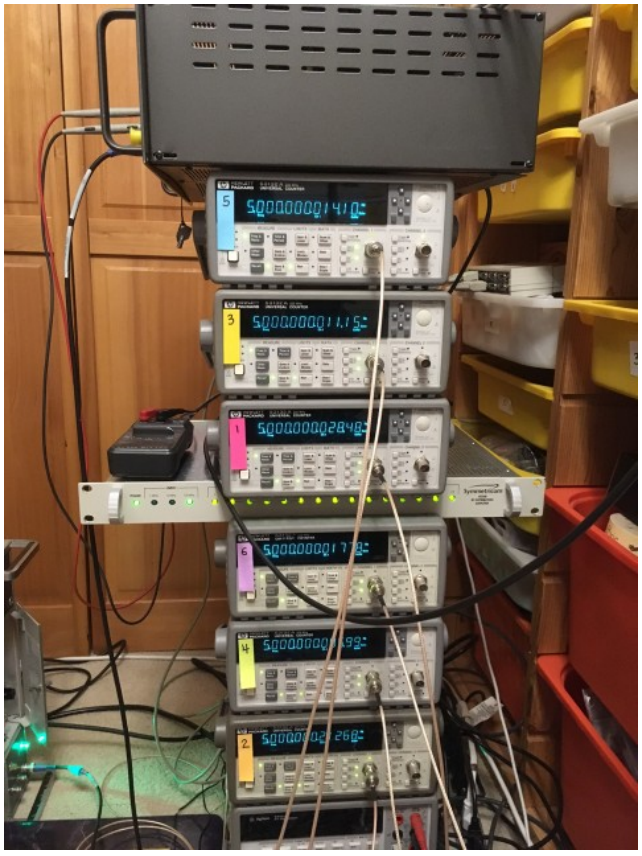
- National Co, 1956-1960
  - first commercial cesium
  - 7 feet (2 m) tall
  - 500 (200 kg) lbs
- "½ s in 30 years" = 5×10^{-10}
- 50 made, few exist





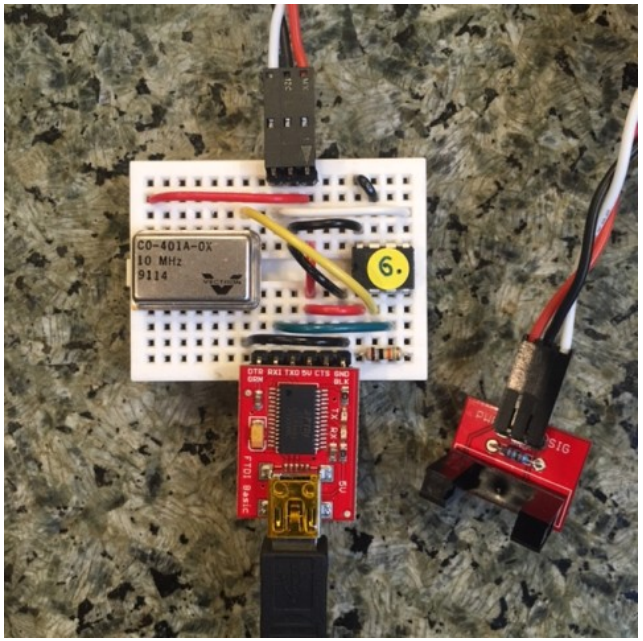
Oscillator stability and drift measurements

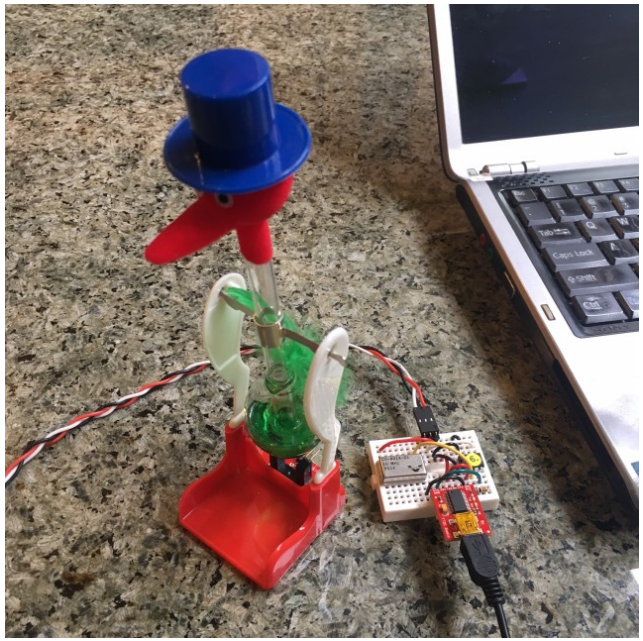
- Measuring 12+ oscillators this week
  - small OCXO, vintage OCXO, expensive BVA OCXO
  - *hp* 5065A, Efratom FRK, FEI Rb, pendulum clock, bird clock



Drinking bird (clocks)

- Birds swing ~1 Hz and drink every ~30 s
- Variation among birds: 28.9 s, 36.2 s, 29.8 s
- Common mode environmental effects:
  - temperature, humidity, barometric pressure, *water level*
- Can use Stable32 / TimeLab to process clock data





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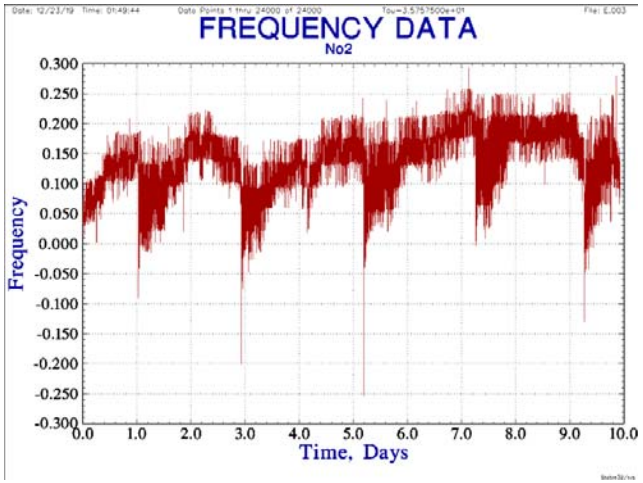
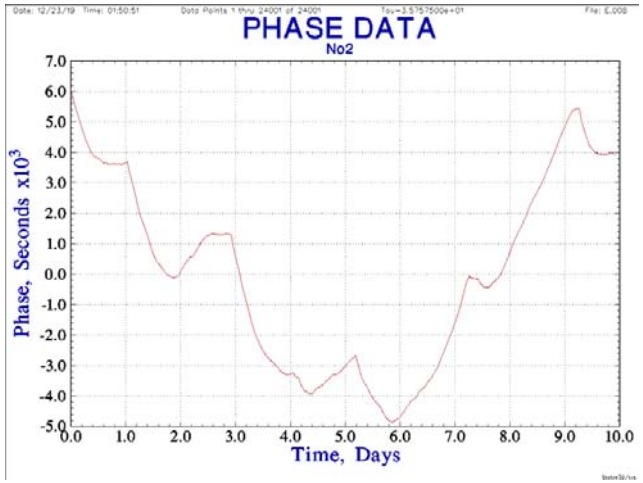
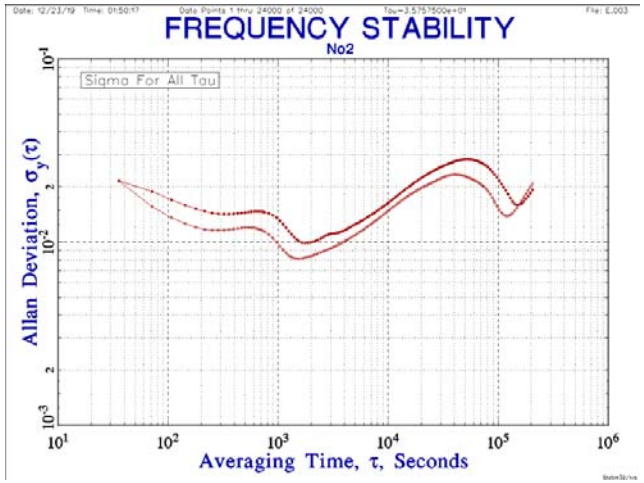


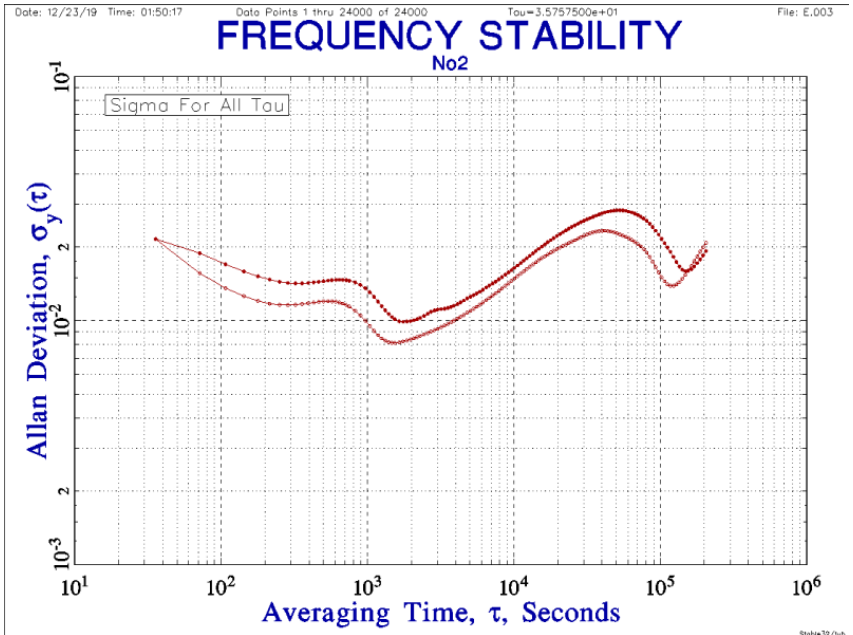


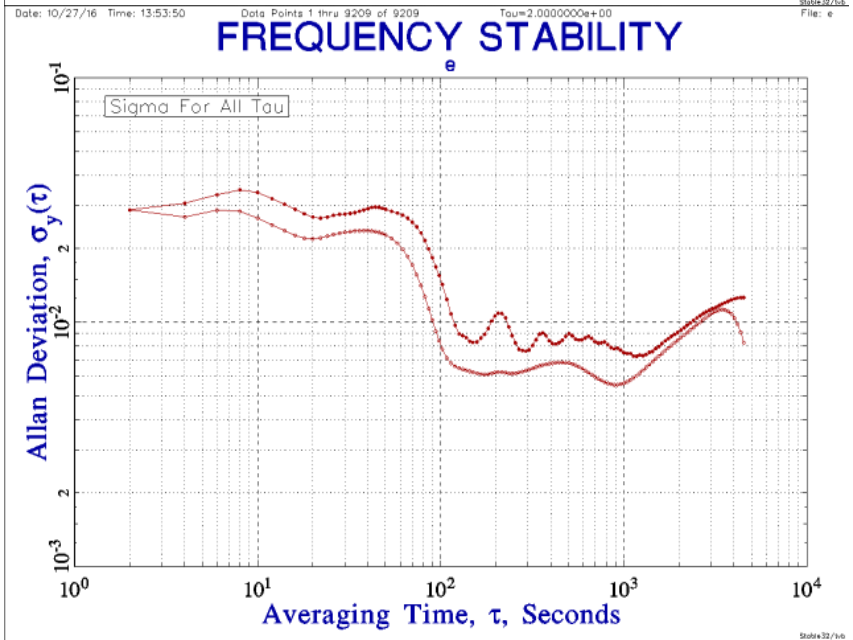


Many types of clocks

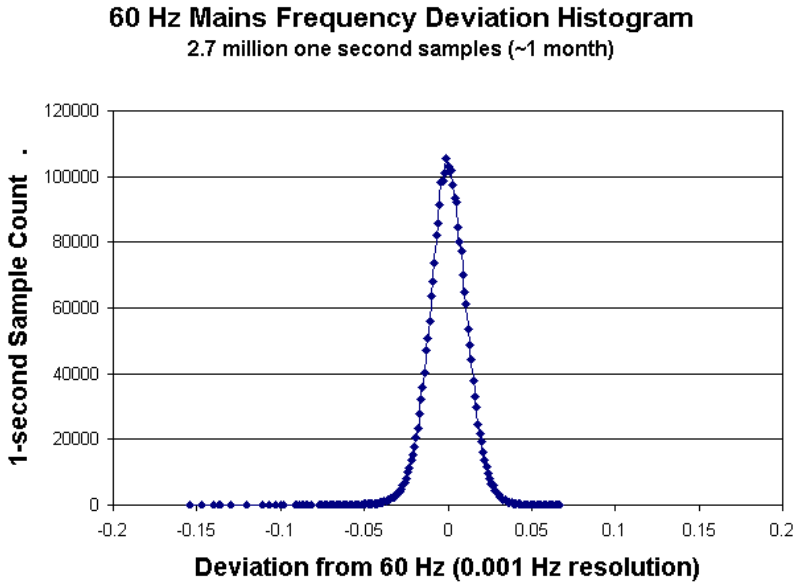
- A clock is based on a repeating pattern
  - vibration, oscillation, rotation, dripping, blinking, etc.
- Keep time by counting those periods
  - using wheels, gears, electronic counter circuits
  - mechanical dial with hands, or electronic digital display like Nixie, LED, LCD, VFD, etc.
- Clock accuracy (stability) ranges:
  - Hours or minutes / day, 10^{-0} to 10^{-2}
  - seconds/day, 10^{-3} to 10^{-5}
  - milliseconds/day, 10^{-6} to 10^{-8}
  - microseconds/day, 10^{-9} to 10^{-11}
  - nanoseconds/day, 10^{-12} to 10^{-14}

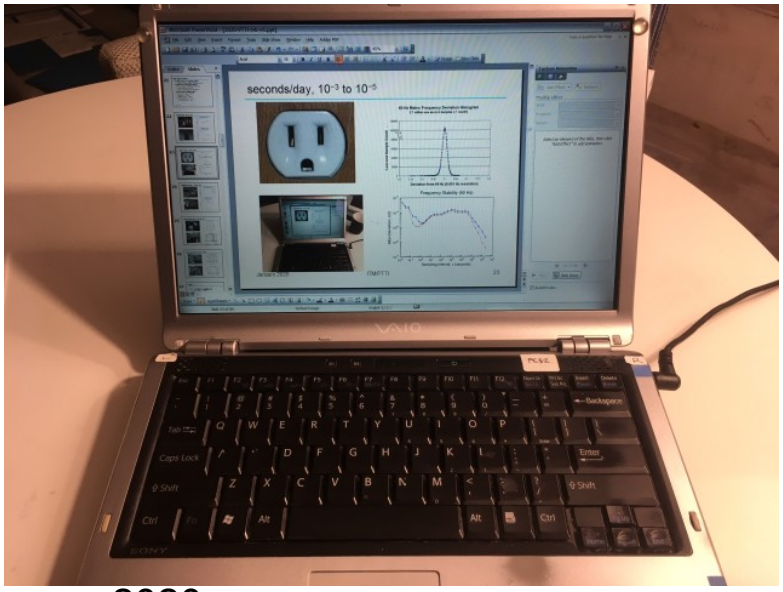
minutes/day, 10^{-0} to 10^{-2}

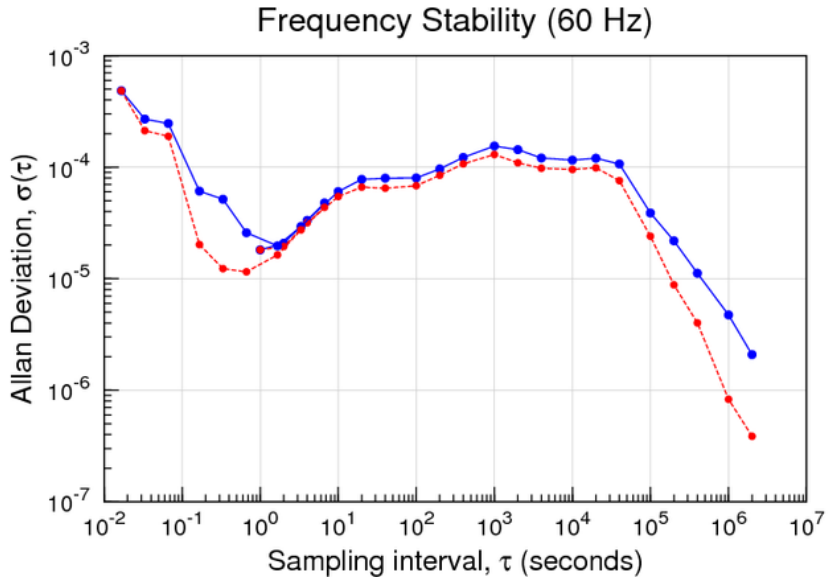




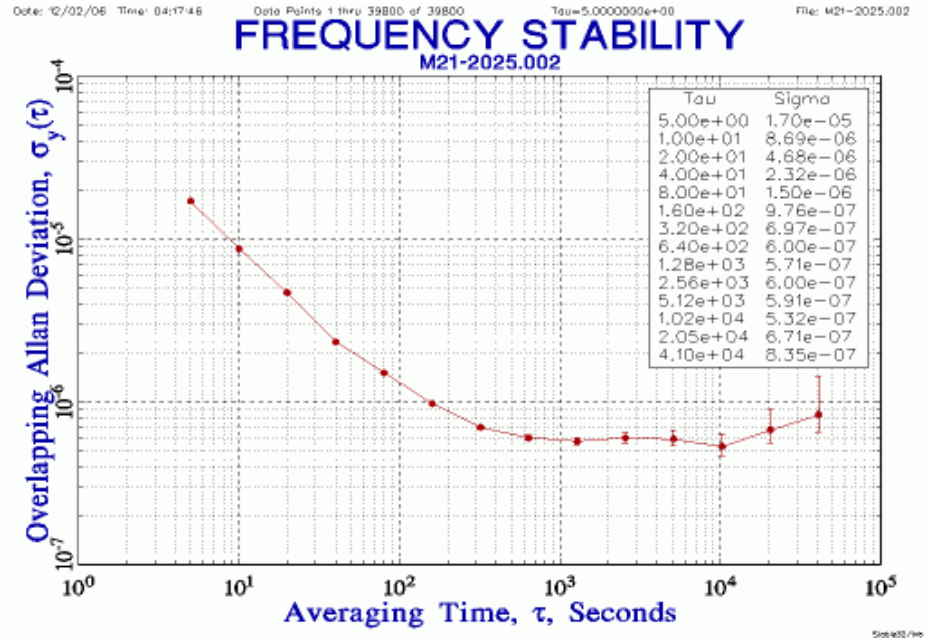
seconds/day, 10^{-3} to 10^{-5}

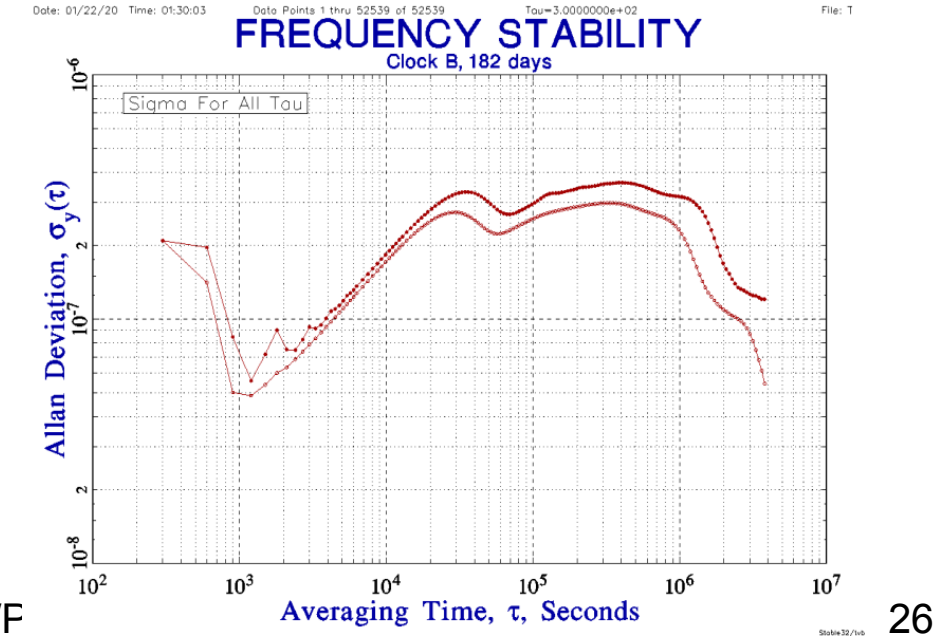




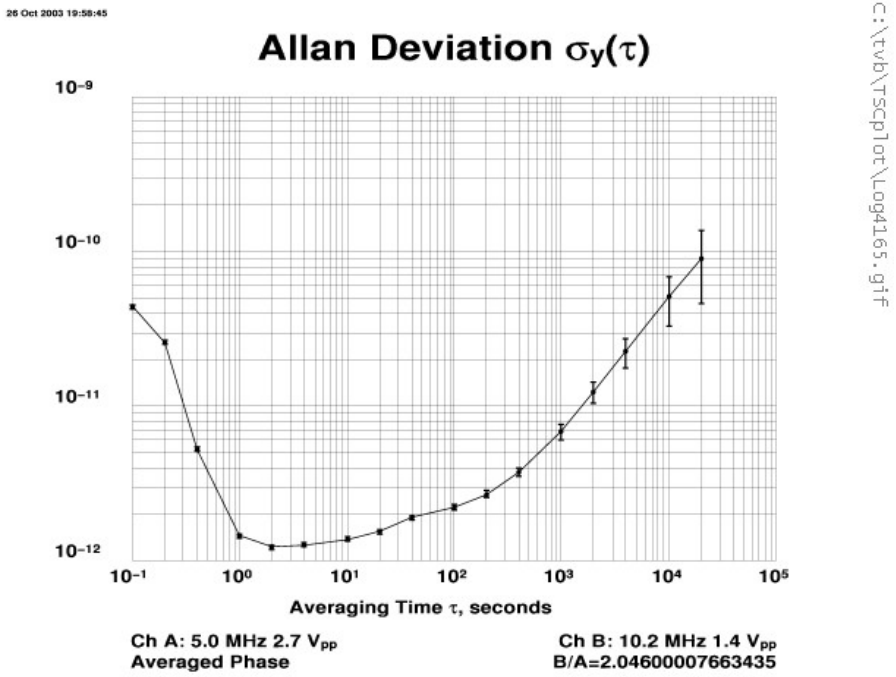


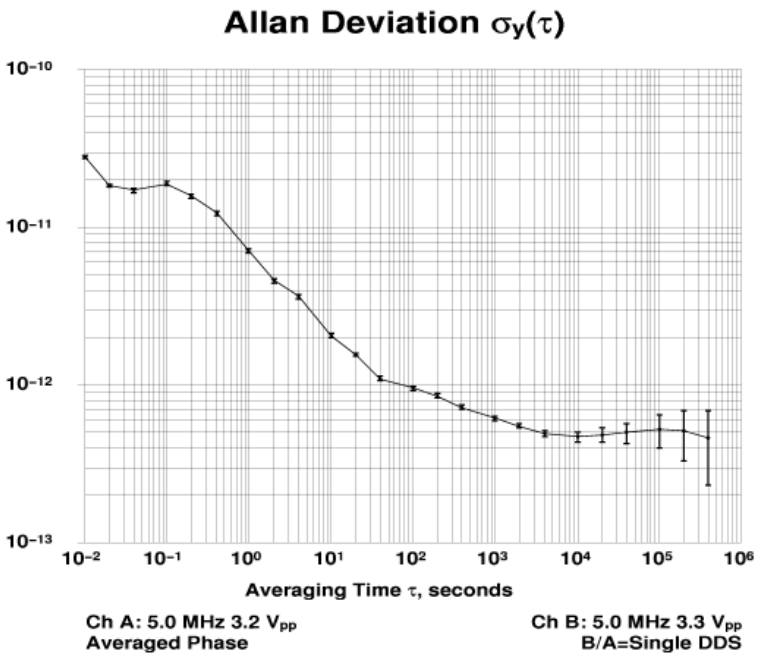
milliseconds/day, 10^{-6} to 10^{-8}



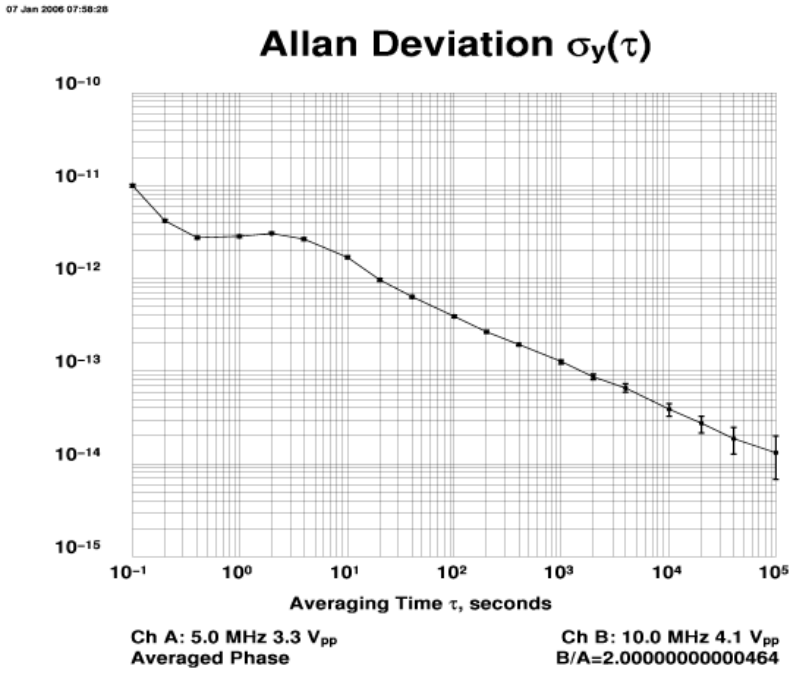


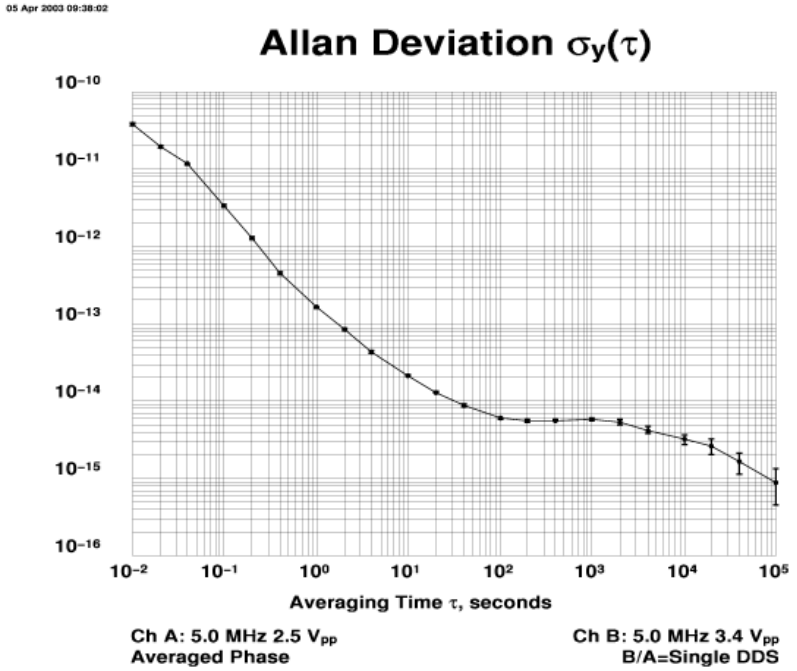
microseconds/day, 10^{-9} to 10^{-11}





nanoseconds/day, 10^{-12} to 10^{-14}





How to make an atomic wristwatch?

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- Part 1 – Navigation and traveling clocks
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Hobby, sharing, community

- Slippery slope!
  - relatively inexpensive, *time*-consuming hobby
  - easy entry, somewhat addictive, first one often free
  - measurement concepts work just as well at $1 as $1000
  - buy, build, repair, sell, trade, collect interesting gear
  - massive trove of military and telecom surplus (eBay)
- *LeapSecond.com* (1999)
  - personal web site to share my time & frequency hobby
  - photos, experiments, data, software, lab reports, manuals
  - also: febo.com (John Ackermann), prc68.com (Brooke Clarke), ke5fx.com (John Miles), and many other web sites and blogs…
  - google does well finding these resources

Hobby, sharing, community

- *Time-Nuts* mailing list (2001)
  - classic email-style mailing list, in its 20th year
  - grown to 1800 members, now a solid, informal community
  - amateur precise time & frequency related topics
  - “low volume, high SNR”, averaging 12 postings/day
  - rich message archive, now >100k messages
  - info: http://leapsecond.com/time-nuts.htm
- Amateur s/w: mostly same as professionals
  - Stable32.exe (Bill Riley), TimeLab.exe (John Miles)
    Plotter.exe (Ulrich Bangert), Heather.exe (Mark Sims)
    AllanTools.py (Anders Wallin), adev_lib.c (Tom Van Baak)
- Amateur h/w: mostly from eBay or DIY projects

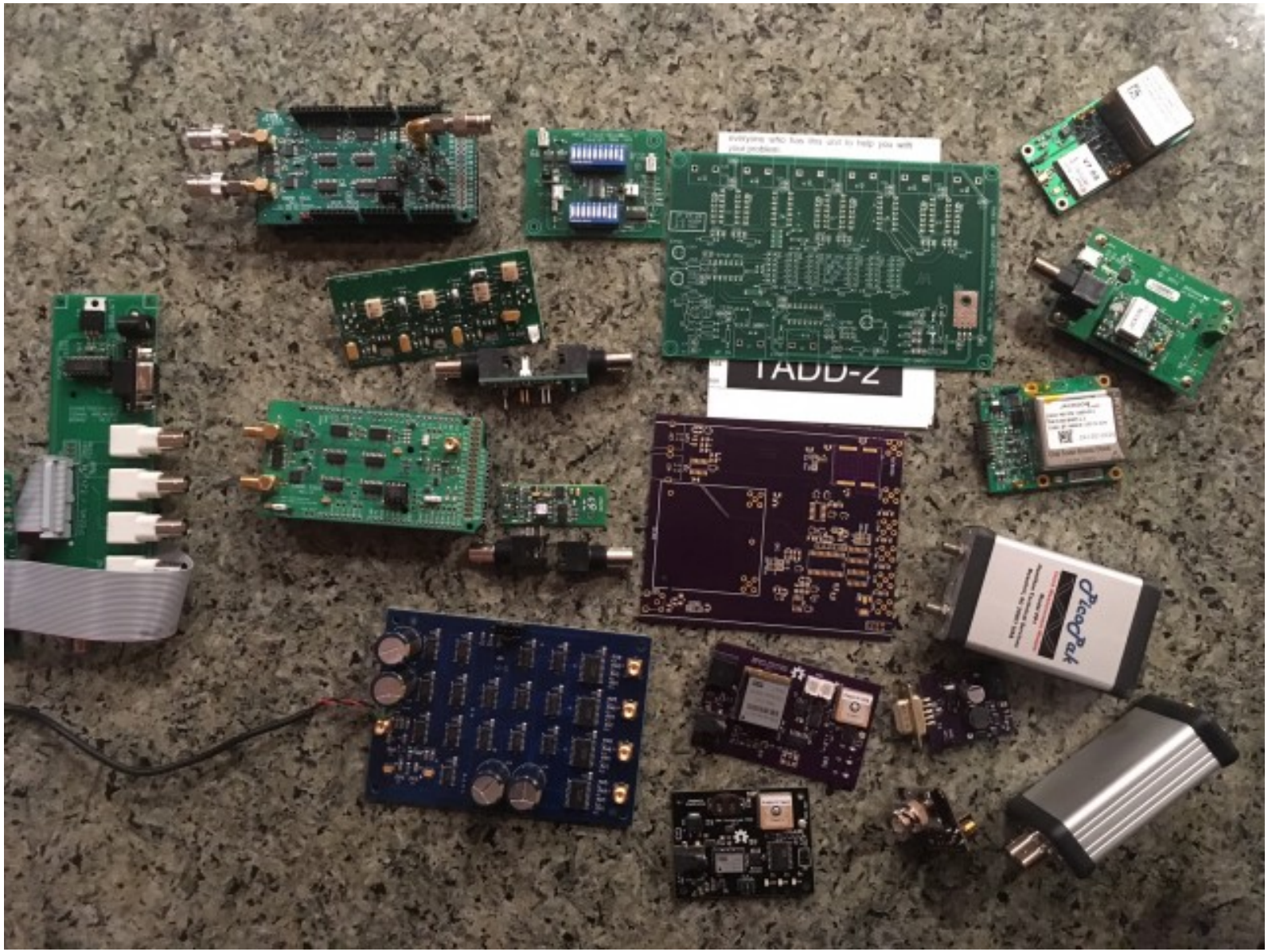
Time-Nuts mailing list: typical subjects

- **1 PPS accuracy** in two locations
- 100 MHz decade **divider** advice needed
- 10811 performance **10 MHz** dist amps
- 15 MHz in 10 MHz out?
- 5 MHz to 10 MHz and **25 MHz**
- **5065A** photo/lamp problem
- 5065A phase-noise
- **88Sr+ ion-clock** live stream
- A simple sampling **DMTD**
- Another **hydrogen maser** success story
- Antique **pendulum** clocks
- Beginner's Atomic Clock
- Building a DMTD/**phase noise** set in the 21st century
- can of worms: **time-of-day** in a community radio station
- Capturing **NMEA** and TICC **timestamp** data in time-correlated way?
- Cold Rubidium?
- DAC for OCXO **disciplining**
- DC **distribution** (Anderson PowerPole)
- Dead 5061B
- Difference in **GPS antennas**
- Do ordinary clouds adversely affect **GPS reception**?
- DST change on **DCF77**
- EFOS B Hydrogen maser arrived
- Even Seconds Pulse option (1PP2S), HP 58503B
- **GPS Antennas**
- GPSDO 10MHz steering **resolution**
- GPSDO+PC as a **NTP** server

Time-Nuts mailing list: typical subjects

- **HP 5065A** owners, a question!
- HP OCXO's 10544A and 10811A
- **HP 5071A** with bad tube.... can I get one used?
- IERS leap second bulletins?
- Keysight N5511A - **phase noise measurements** down to theoretical-177 dBm/Hz
- **Low Phase Noise** Amplifiers
- Lowest Power **NTP** Server
- Phase **Microstepper**
- Norton amplifiers
- **OCXO** pressure sensitivity before TCXO
- Odd-order **multiplication** of CMOS-output OCXO
- Phase Detectors/Mixers for **DMTD** and PN measurements
- **PLL** suggestions
- PRS-10 Missing SP values in Appendix A.
- **Quadrature** Phase Noise Measurement
- Question for my new **GPSDO**
- **Raspberry Pi** TCXO Hat
- signal transit time through **WWV** receiver
- **Synchronization**
- TAPR TIC Upgrade?
- The **difficulty of low noise measurements**
- The **TAI** zero epoch of 1958
- Trimble TBolt temperature
- Two free **Cesium** Standards
- uBlox **F9T** testing - best settings?
- u-Blox ZED-F9T block diagram or timing
- Using HP5071A with **dead tube** along with GPS
- Wall Clock that takes **1PPS** input

DIY h/w examples, mostly TAPR

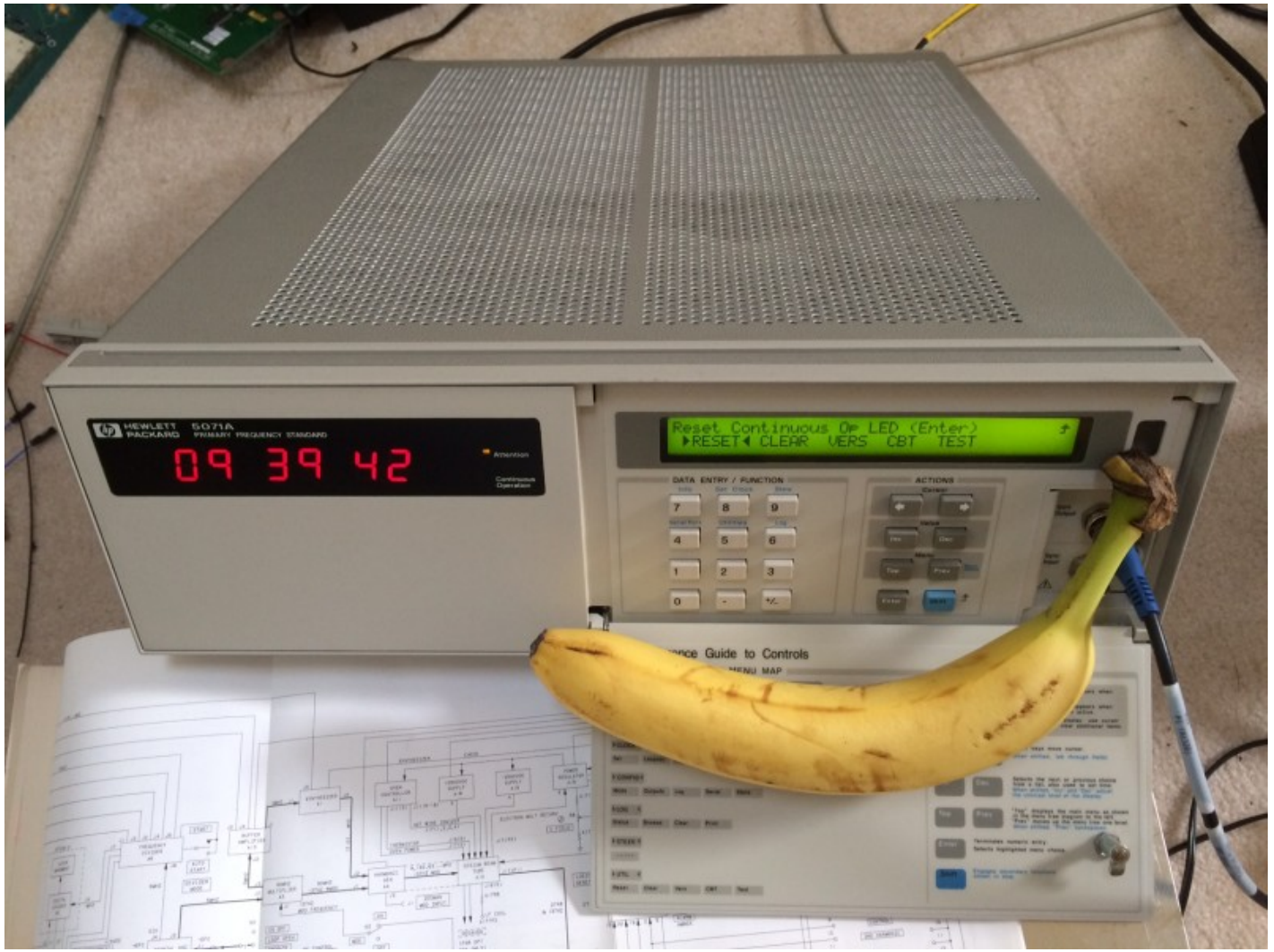


Atomic clock hobby: common questions

- Where do you get all this stuff?
  - Almost everything is from eBay, over years, decades
- How do you set the time of an atomic clock?
  - Loran-C, WWVB / DCF77, NTP, GPS
- How do you get the best clock?
  - Get one clock. Get another clock, compare, repeat
- What's the point?
  - Fascinating mix of history, technology, metrology, challenge
- Are cesium atomic clocks safe?
  - Yes, Cs^{133} atoms are natural and stable (Cs^{137} is radioactive)
  - Also C^{12} (safe) vs. C^{14} (dating) or K^{39} vs. K^{40} (banana)

How to make a cesium clock radioactive?

- Just add a banana…



FAQ: How to set the time?

- Frequency or *time interval* is defined (SI unit)
- Time or *time of day* is social convention (UTC)
- Even best atomic clock blinks “12:00” on power-up
- Ways to set your clock
  - sundial during day, stars at night
  - WWV short-wave
  - WWVB / DCF77
  - NTP (internet)
  - GPS / GNSS
- Strong interest in GPS/1PPS, time transfer, GPSDO

FAQ: Relativity & GPS

- GPS flight is extreme:
  - speed 14,000 kph, 8,700 mph, Mach 12, 0.000013 c, "13 μc"
  - altitude 20,000 km, 12,500 miles (~3× R_e)
- Large relativistic effects occur:
  - $\Delta f/f = -8.4\times10^{-11}$, or $\Delta t/T = -7.3$ μs/day (kinematic)
  - $\Delta f/f = +5.3\times10^{-10}$, or $\Delta t/T = +45.6$ μs/day (gravitational)
  - $\Delta f/f = +4.4\times10^{-10}$, or $\Delta t/T = +38.3$ μs/day (net effect)
  - 10.23 MHz set to 10.229999954326 MHz
- How small is 4.4×10^{-10} ?
  - ~1 ms / month
  - 1 s / ~71 years
  - ~1 atom / 1 meter
  - ~6 inches / distance to Moon
  - ~1 cm^3 / volume of Olympic swimming pool

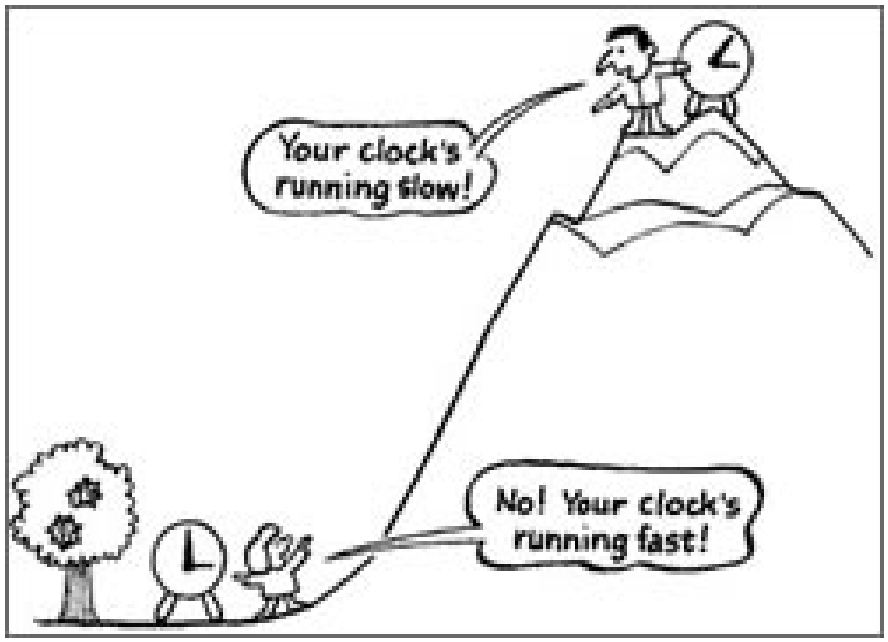
Outline

- Part 1 – Navigation and traveling clocks
  - clocks, timing, the ‘T’ in PNT
- Part 2 – Atomic clock collecting hobby
  - going to extremes at home
- Part 3 – *LeapSecond.com* and *time-nuts*
  - sharing the hobby with thousands
- Part 4 – Project GREAT
  - DIY gravitational time dilation experiment(s)

2005

Clocks, mountain-valley, relativity

- Is relativity detectable at human scale?
  - aka, have I accumulated enough clocks by now?
  - can time dilation be measured by an amateur?
  - can I travel fast enough, or high enough?
  - Mt Rainier is only 100 miles away (2½ hours)



From NPL website

Project GRE²AT

- **G**eneral **R**elativity **E**instein/**E**ssen **A**nniversary **T**est
  - 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
- 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

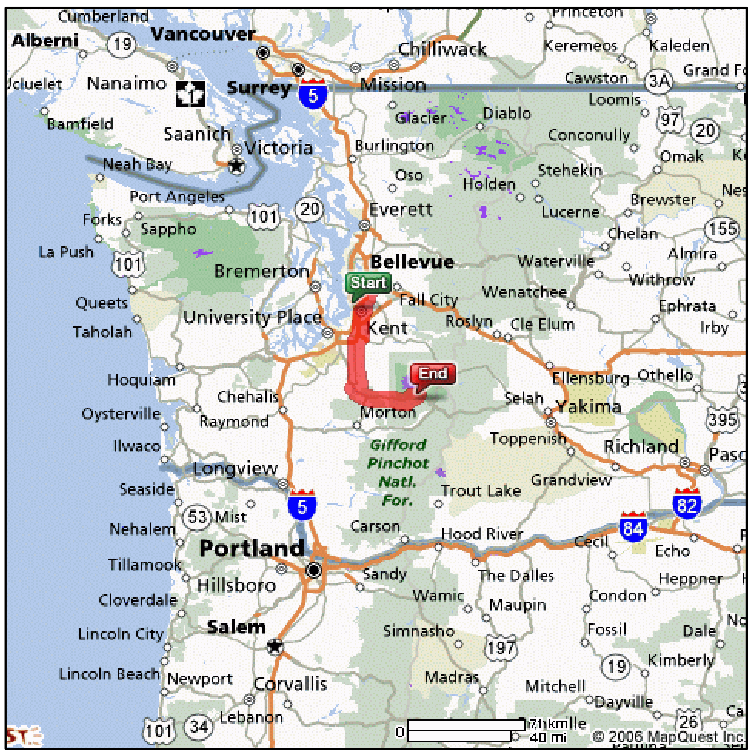
  $\Delta f/f = 1.1\times10^{-13} = 0.11$ ps/s

  note: 4000× less than GPS
- And if you stay up there 24 hours, then

  $\Delta T = \Delta f/f \times 86400$ s $= 9.5\times10^{-9}$ s $= 9.5$ ns
- Rule-of-thumb: 1 km elevation ≈ 10 ns/day

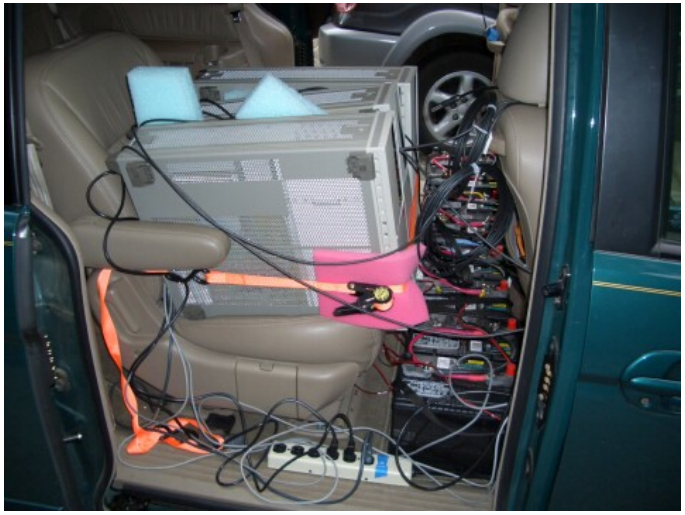
How to magnify 0.00000000000000001?

- S/N ratio:
  - go as **high** as possible
  - stay as **long** as possible
  - measure **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


GARMIN
foretrex 101
LOCATION
N 47°33'15.7"
W122°08'22.4"
ELEVATION
1035 ft
goto page enter
mark

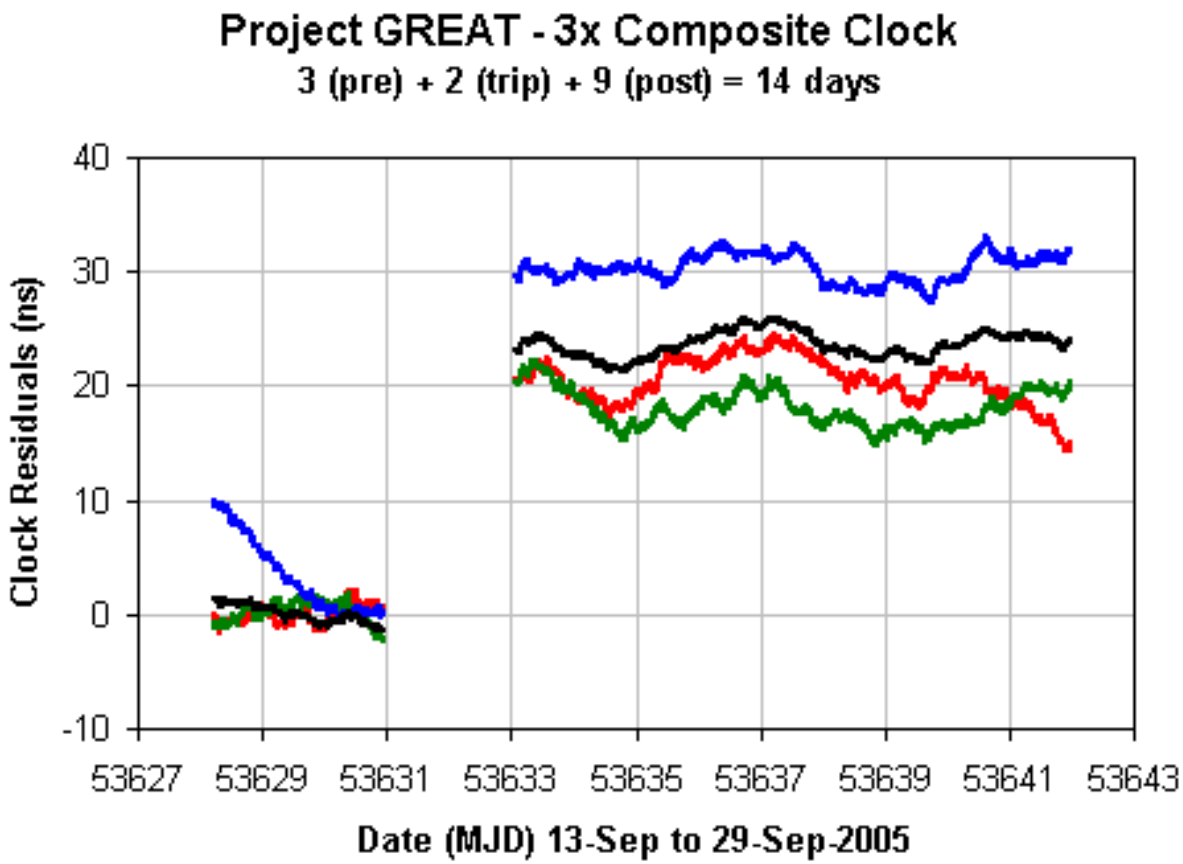



Paradise Inn
Parking
Area Reserved For
Registered Overnight
Guests Only


GARMIN
foretrex 101
LOCATION
N 46°47'11.0"
W121°44'05.9"
ELEVATION
5419 ft
goto page enter
mark

Time dilation: predicted vs. measured

- Prediction, based on elevations and duration
  - Δh = 5400 ft – 1000 ft = 4400 ft (1340 m)
  - ($\Delta f/f \approx g\Delta h/c^2$) 1.46×10^{-13} times 42 hours = +22.4 ns
- Measured, based on 3 clock mean (black = R+G+B)
  - ΔT = +23.2 ±4 ns



Project GRE²AT – summary

- Einstein was right; time dilation is real!
  - clocks (and we) came back 22 ns **older**
  - this is gravitational effect (elevation, *not* velocity)
  - PTTI evening presentation (2006)
  - unexpected press: WIRED, Physics Today, Reddit, Scientific American, blogs, even a physics textbook…
- Conceptually simply experiment
  - easier (but different) than Hafele-Keating
  - much cheaper (but far less accurate) than GP-A
  - no black boxes, no ambiguity, “anyone can do it”
  - yes, now *”relativity is child’s play”*

2016

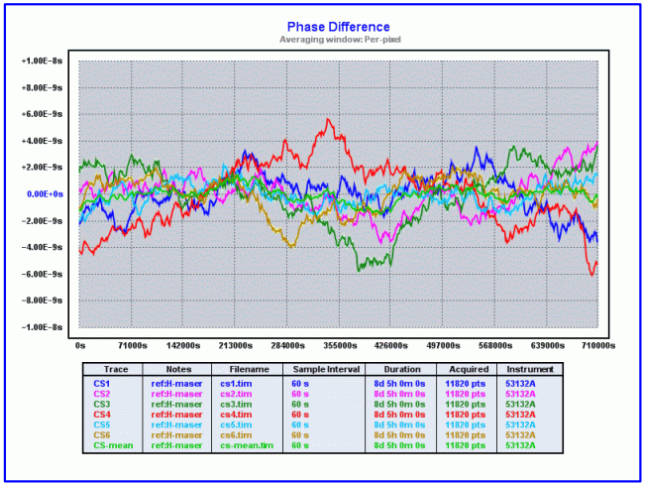
GREAT 2016a – Mt Lemmon, AZ

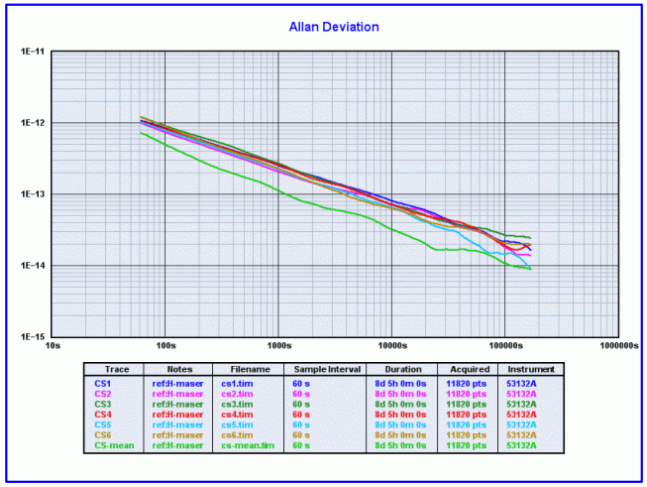
- Stephen Hawking “GENIUS” series
  - for PBS, BBC TV
  - episode on space-time, clocks, “time travel”
  - asked me to help
- Mt Lemmon, AZ
  - 9160 ft (2790 m) summit
    2600 ft (790 m) base
  - UK film crew and “cast”
    January 2016 (winter)

- Δh 2000 m × 24 hours = ~20 ns time dilation
  - 3+3 cesium clocks, 1600 miles away from home lab
  - tight schedule, no re-takes, *“failure is not an option”*

2016a – from Bellevue, WA

- Test and synchronize 6 clocks for a few weeks, load car, drive 1600 miles from Bellevue to Tucson

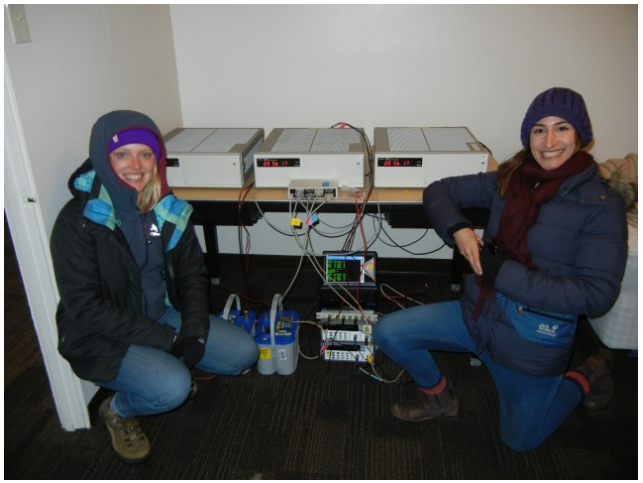




2016a – to Tucson, AZ

- 3 mountain clocks (Mt Lemmon summit), 3 valley clocks (Tucson hotel), 3 “genius” participants



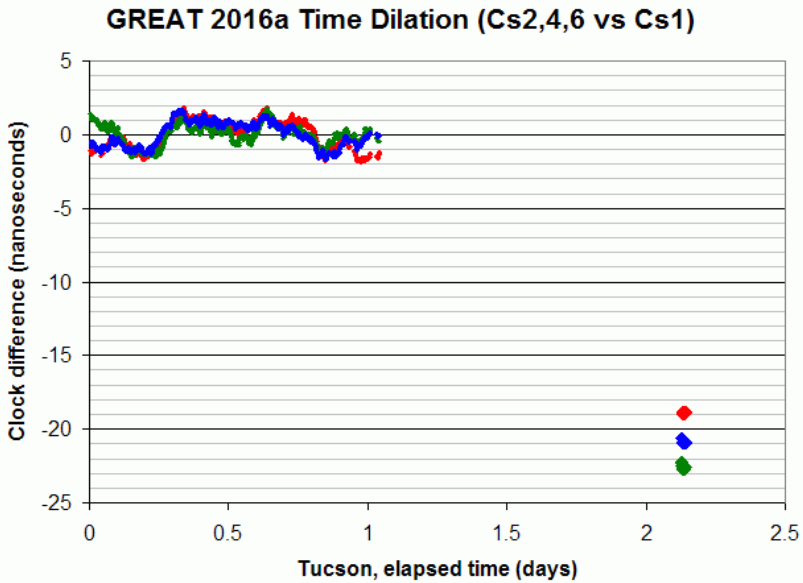



2016a – results

- It worked! (much relieved)
  - stand-alone experiment
  - different mountain, elevations, different latitude, duration
  - up-down-up vs. down-up-down
- 2 months work for 20 ns result

  RIP Stephen Hawking (1942–2018)
- Show available on iTunes or *pbs.org*

  www.pbs.org/genius-by-stephen-hawking/episodes/episode-1/

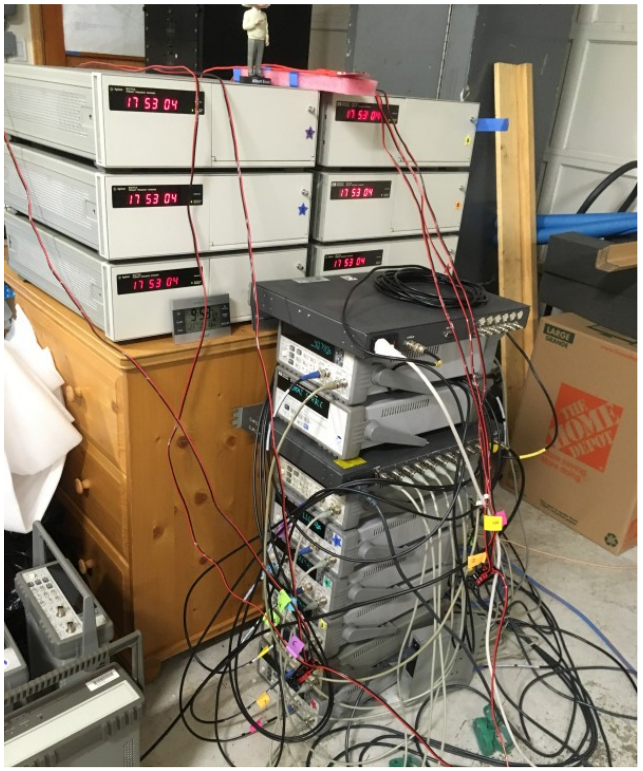


"To see the time difference I've arranged for a world expert on clocks to loan them some impressive equipment"

2018

GREAT 2018a – Palomar Mountain, CA

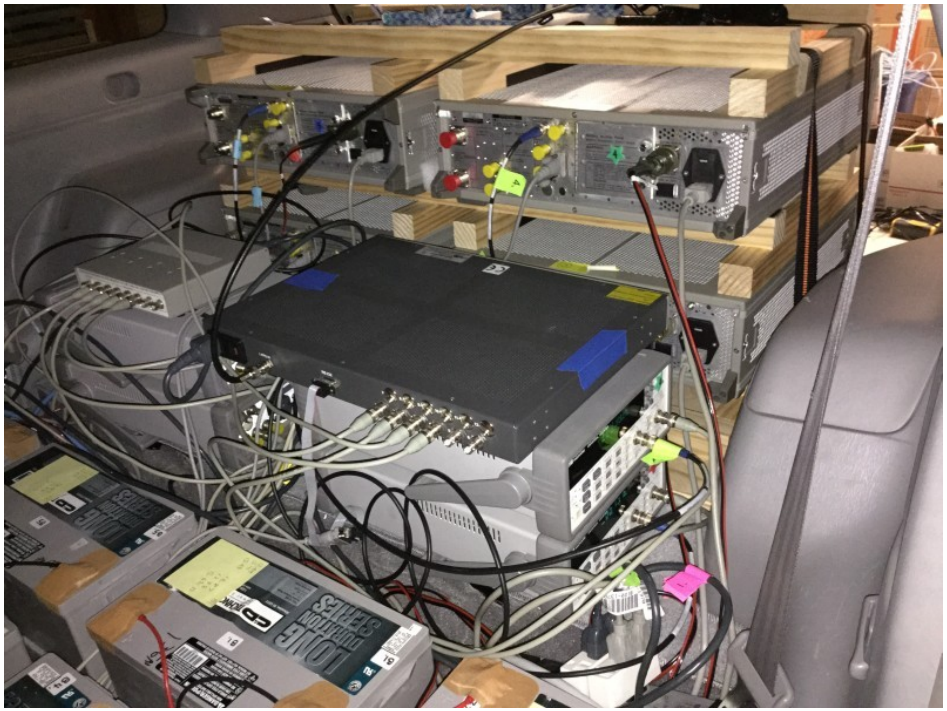
- History Channel, “In Search Of”, Zachary Quinto
  - “time travel” episode, demonstrate time dilation
- Southern California location
  - low clocks: Oceanside (~sea level)
  - high clocks: Palomar Mountain (~5500 ft)
- Logistics
  - using 2+2 cesium clocks
  - 1250 mile drive down on I-5
  - 24 hours at summit of Palomar
  - predicted time dilation: Δh 1600 m × 24h = ~15 ns
  - unscripted, quasi-scientific, reality TV



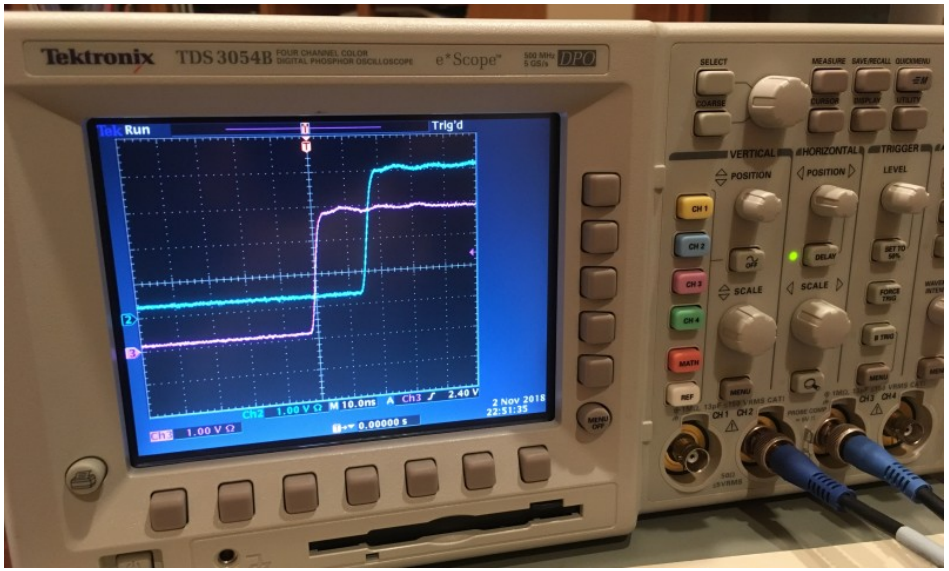


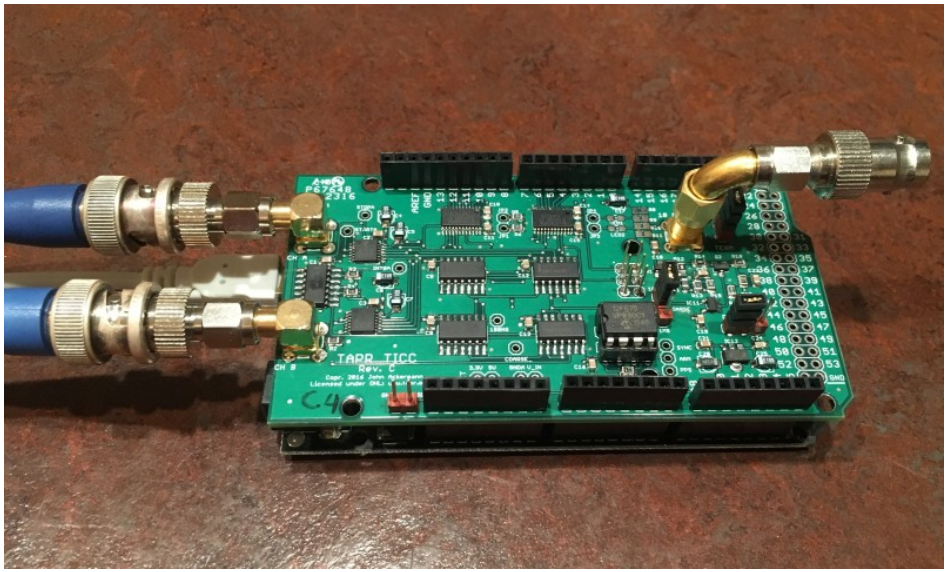


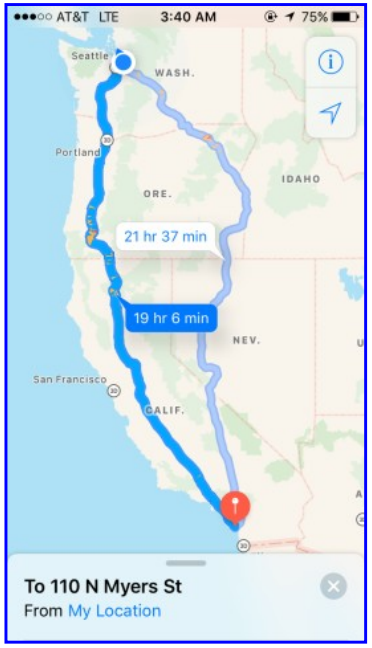
EnerSys



Comparing clocks / nanosecond

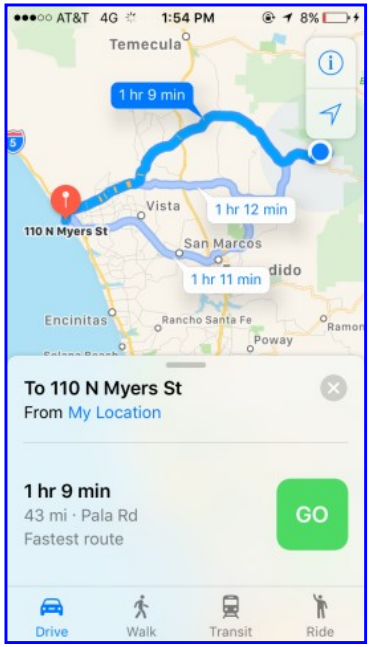





AT&T LTE 3:40 AM 75%
Seattle
WASH.
Portland
ORE.
IDAHO
21 hr 37 min
19 hr 6 min
NEV.
San Francisco
CALIF.
To 110 N Myers St
From My Location


SPRINGHILL SUITES Marriott

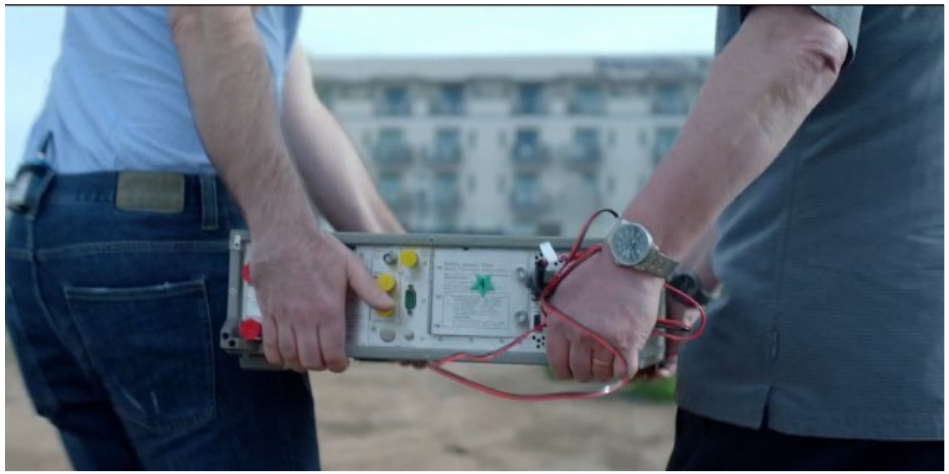

AT&T LTE 10:23 AM 88%
88ft
GPS data +/-9ft


AT&T 4G 1:54 PM 8%
Temecula
1 hr 9 min
Vista
1 hr 12 min
110 N Myers St
San Marcos
1 hr 11 min
Encinitas
Rancho Santa Fe
Poway
To 110 N Myers St
From My Location
1 hr 9 min
43 mi · Pala Rd
Fastest route
GO
Drive
Walk
Transit
Ride

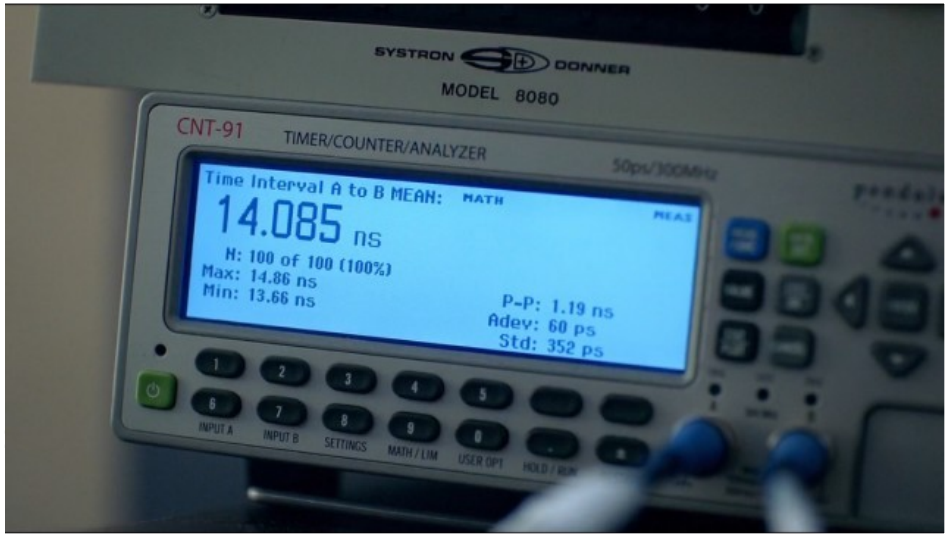

ELEVATION 5550 FT
SAN DIEGO S6 COUNTY
END
CALIFORNIA INSTITUTE OF TECHNOLOGY
PALOMAR OBSERVATORY
VISITOR PARKING
ELEVATION 5550 FT.
HOURS 9 AM - 3 PM


BAILEY'S


No Service 11:38 AM 52%
Touch to return to Navigation
5324ft
GPS data +/-9ft




ELEVATION
5000 FT


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

2018a – results

- Predicted time dilation: 15.5 ns
  - based on recorded elevation and dwell time
- Measured time dilation: 14.1 ns
  - Cs#1 to Cs#4: 14.3 ns
  - Cs#3 to Cs#5: 13.8 ns
- Show available on iTunes or *history.com*

  www.history.com/shows/in-search-of/season-1/episode-5

2020

Project GREAT summary

- 2005 Mt Rainier (family trip)
  - up-down-up, latitude 47°
- 2016 Mt Lemmon (Hawking, PBS/BBC TV)
  - down-up-down, 9159 ft (2800 m), latitude 32°
- 2018 Palomar Mountain (History TV)
  - up-down-up, sea level, latitude 33°
- Comments
  - nice variety of experiments
  - not too interesting to Science (been there done that)
  - very interesting to amateur science community
  - combines many aspects of time, laboratory, measurement
  - a nice tribute to the portable clock pioneers
  - fun thing to do with a time & frequency atomic clock hobby

Thanks for your time!

- A short tour of a timekeeping hobby
  - old timers and portable traveling clock history
  - collecting, measuring, reading, experimenting, sharing
  - a curiosity turns into a hobby,
    a hobby turns into a community, and
    relativity turns into child's play
- Professional vs. amateur astronomy
  - the same applies for amateur time & frequency metrology
- My deepest thanks to the PTTI community
  - precise timing is increasing in performance, and importance

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

Vast range of clock precision

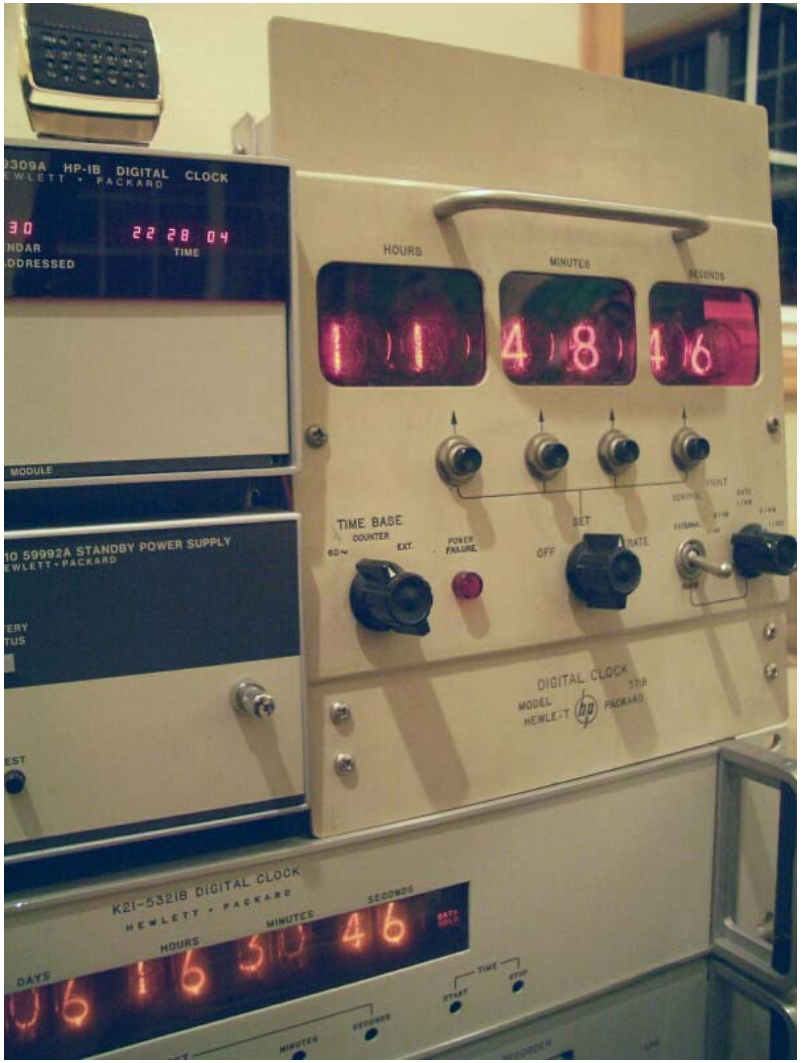
- 10^{-2} = 1% ≈ 15 min / day
- 10^{-4} = 0.01% ≈ 1 min / week
- 10^{-6} = 1 ppm ≈ 0.1 s / day
- 10^{-8} ≈ 1 ms / day
- 10^{-10} ≈ 10 μs / day ≈ 1 s / 300 years
- 10^{-12} = 1 ppt ≈ 100 ns / day
- 10^{-14} ≈ 1 ns / day ≈ 1 s / 3,000,000 years
- 10^{-16} ≈ 3 ns / year ≈ 3 s / billion years
- 10^{-18} ≈ 1 s / 30 billion years

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