A close look at clock ‘B’

and why pendulum clocks are even more interesting than atomic clocks.

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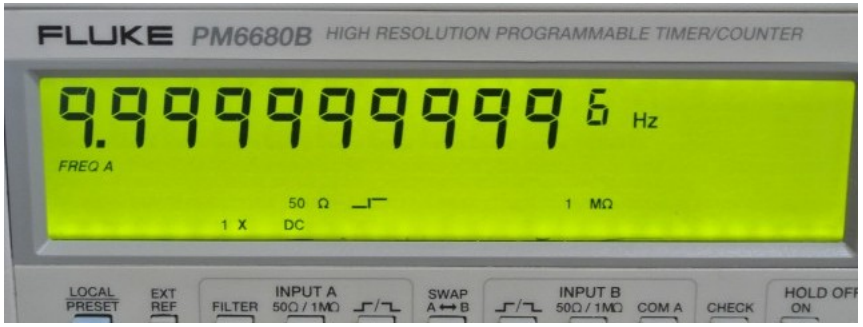
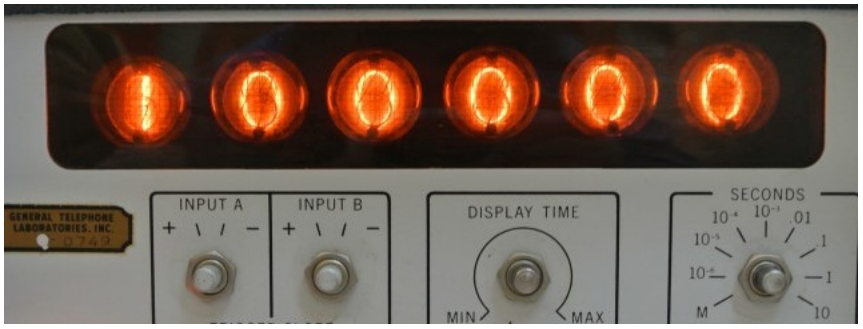
Harrison Decoded Conference
Greenwich, April 2015

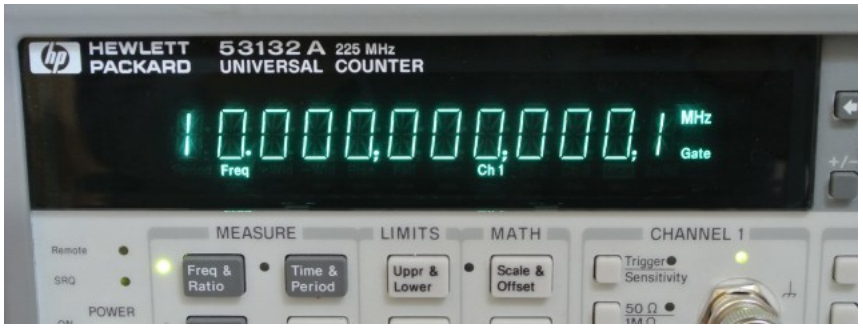
Outline

1. Introduction
2. First look, Clock “B”, 2013
3. In search of the perfect clock
4. Second look, Clock “B”, 2015
5. Pendulum accuracy, P & Q

1: Introduction







Home time & frequency lab

Museum of vintage *hp* clocks

Atomic clock experiments

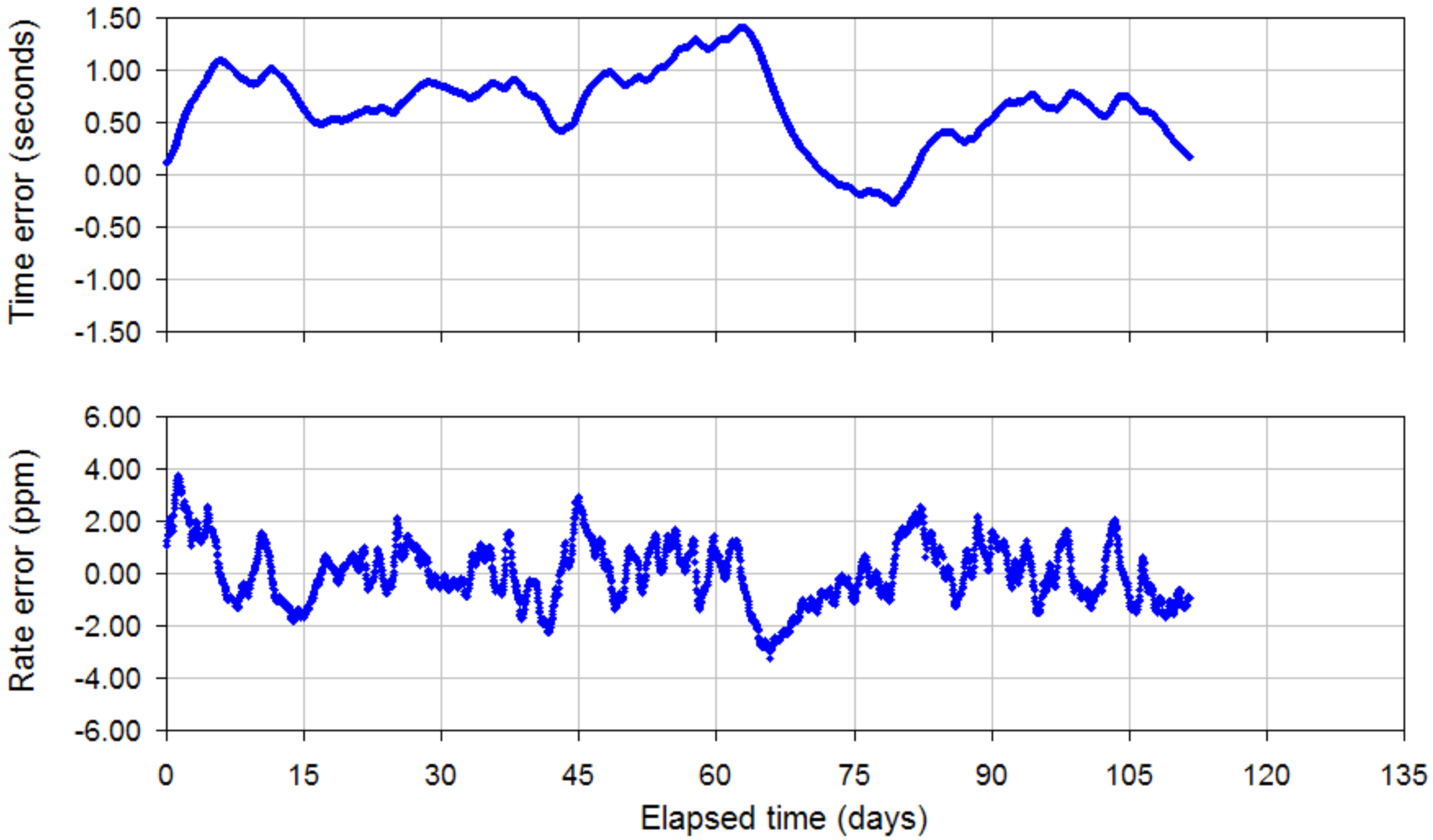
Fashionable atomic wristwatch

Miniature cesium clock (CSAC)

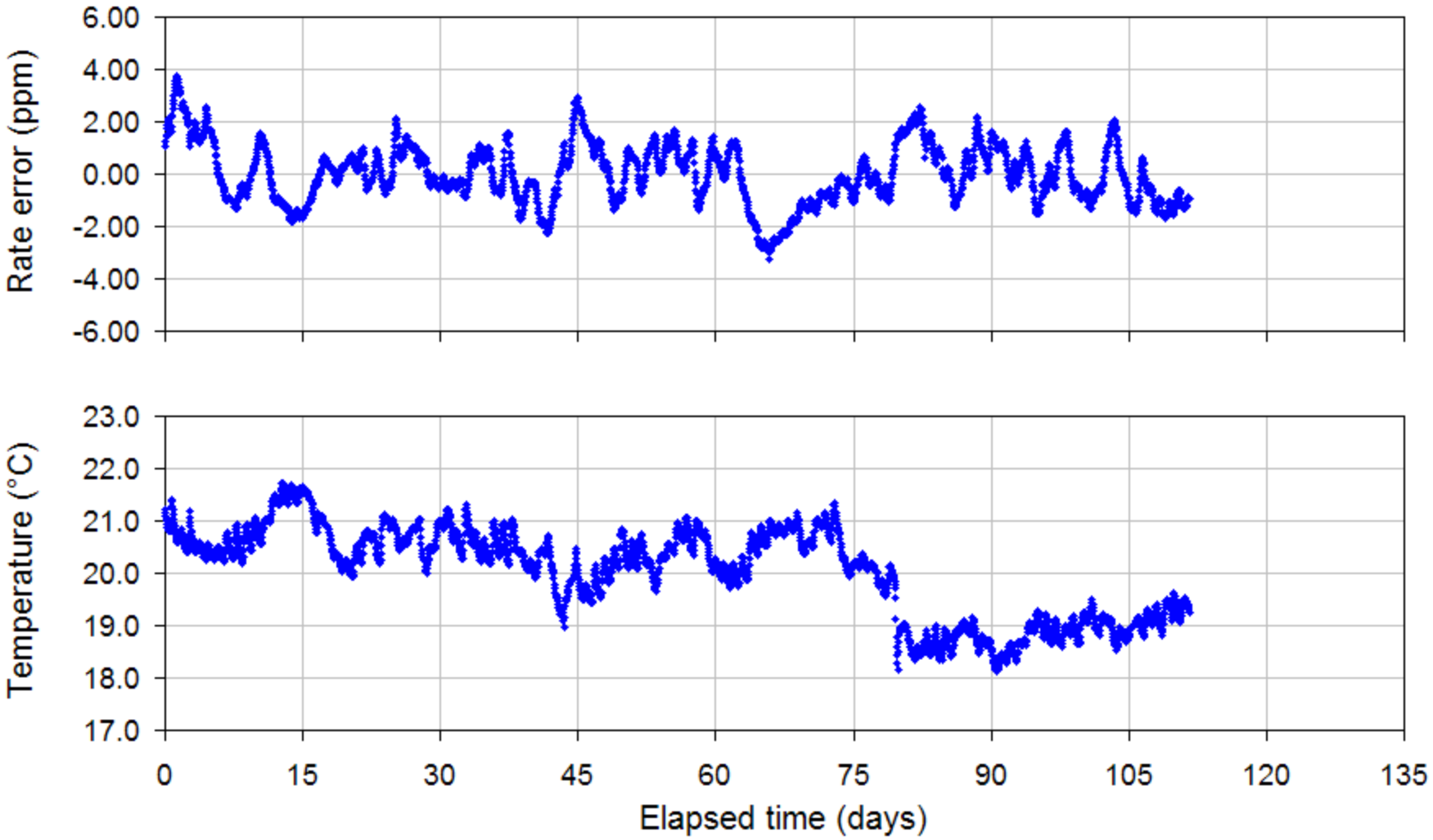
2: First look, Clock “B”, 2013

- Mysterious “Burgess Regulator B”
- Raw Microset / GPS data files
  - 300 second (5 min) samples
  - October 30, 2012 to February 19, 2013
  - 111 days
- N.B. all 2012/2013 plots in **blue**

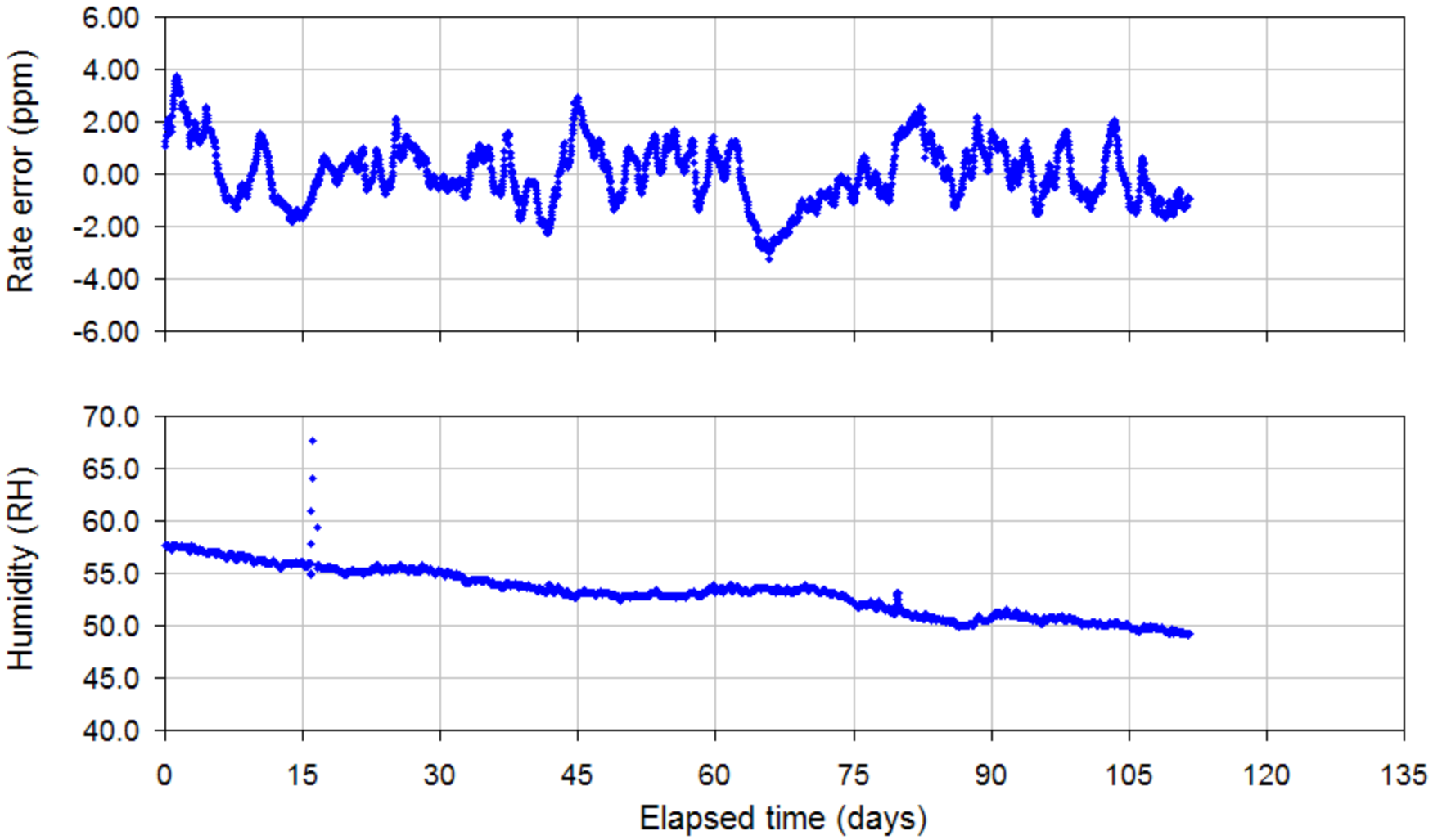
Time drift and rate error (ppm)



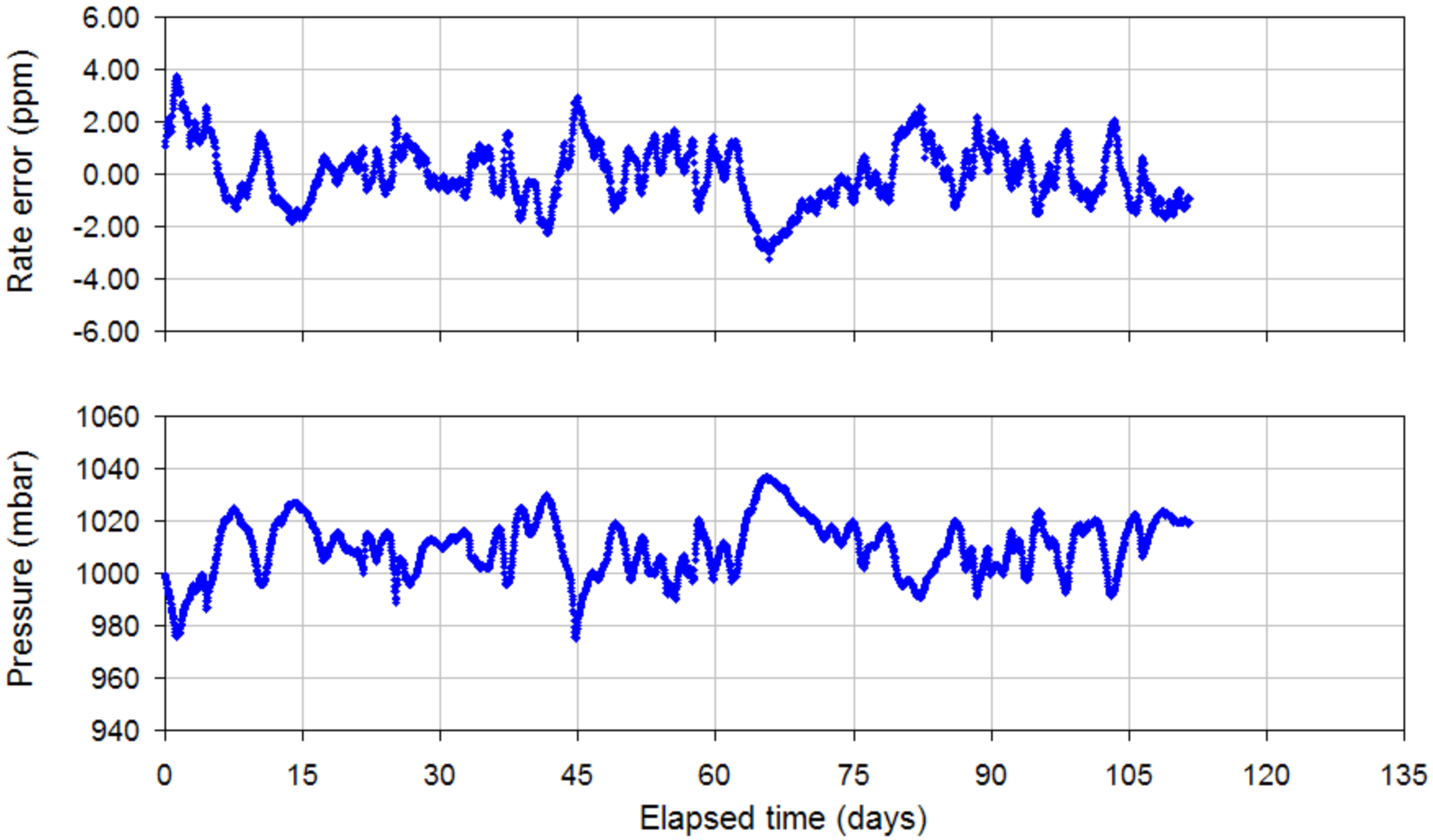
1) rate vs. temperature



2) rate vs. humidity



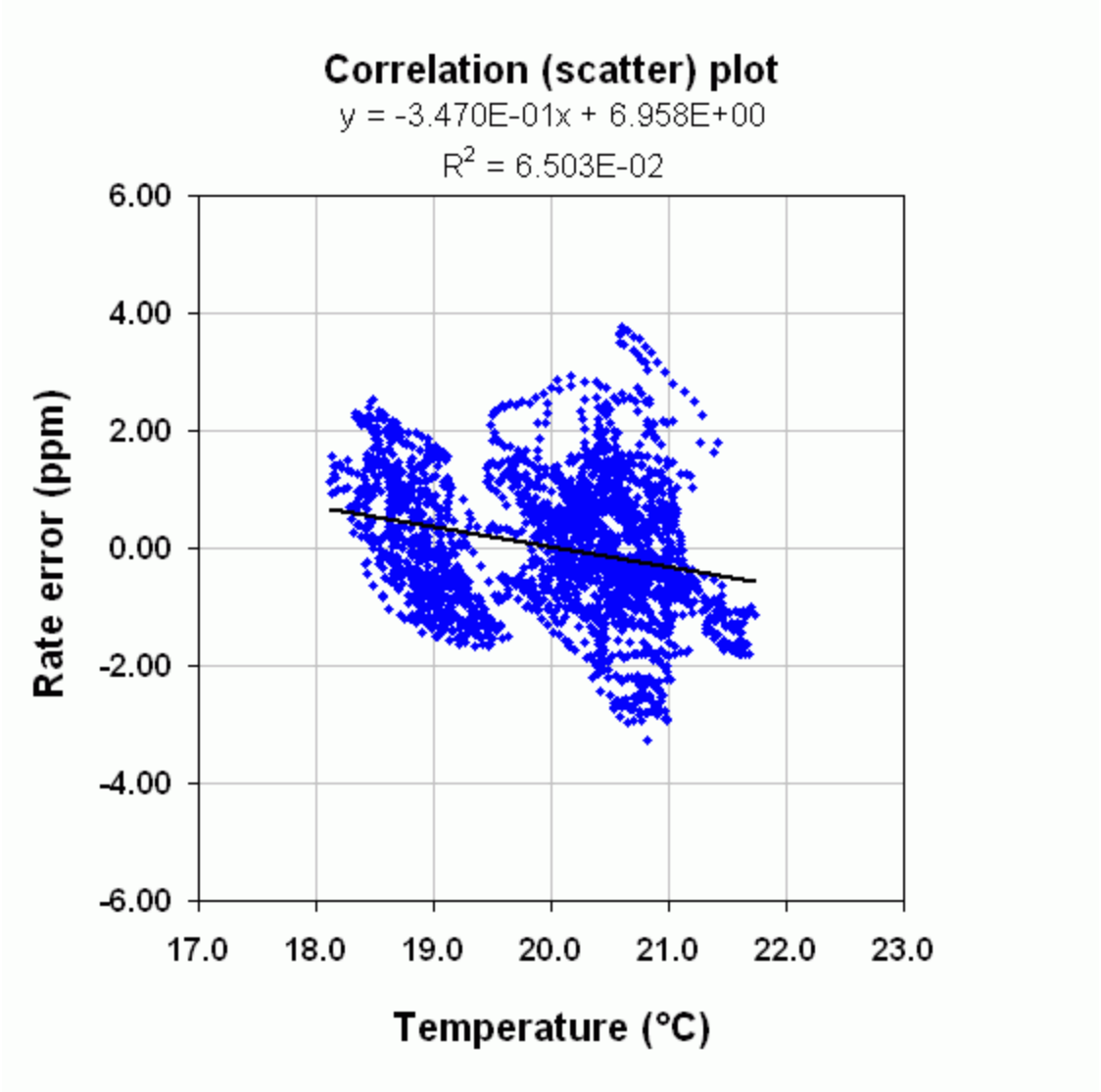
3) rate vs. barometric pressure !



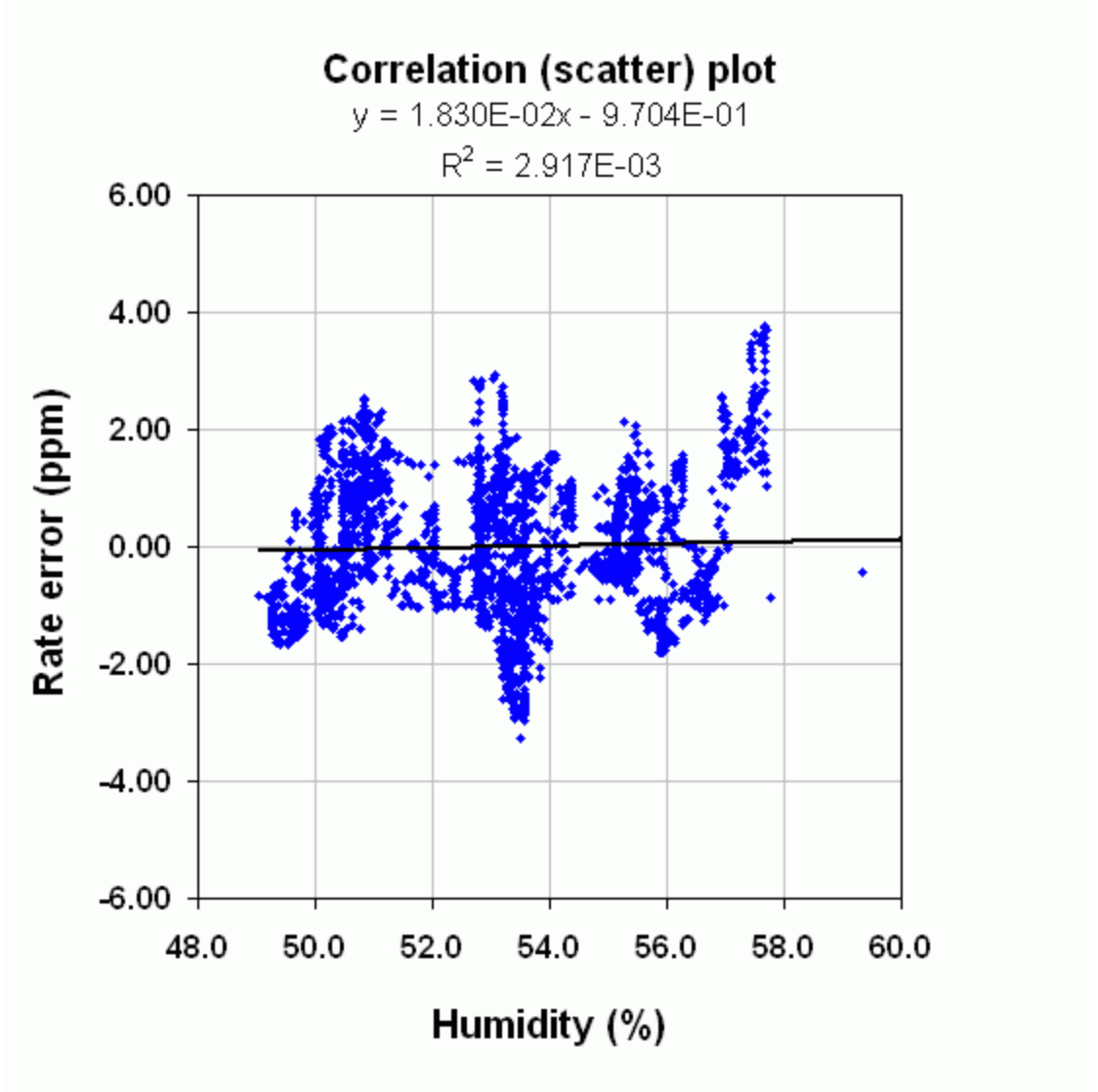
2013 summary

- Amazing mystery clock
  - wanders outside 1 second a few weeks
  - but ends within 1 second in 100 days
  - rate stays within ±4 ppm
- Pretty good compensation
  - very low temperature effect
  - no visible humidity effect
  - largest factor is barometric pressure

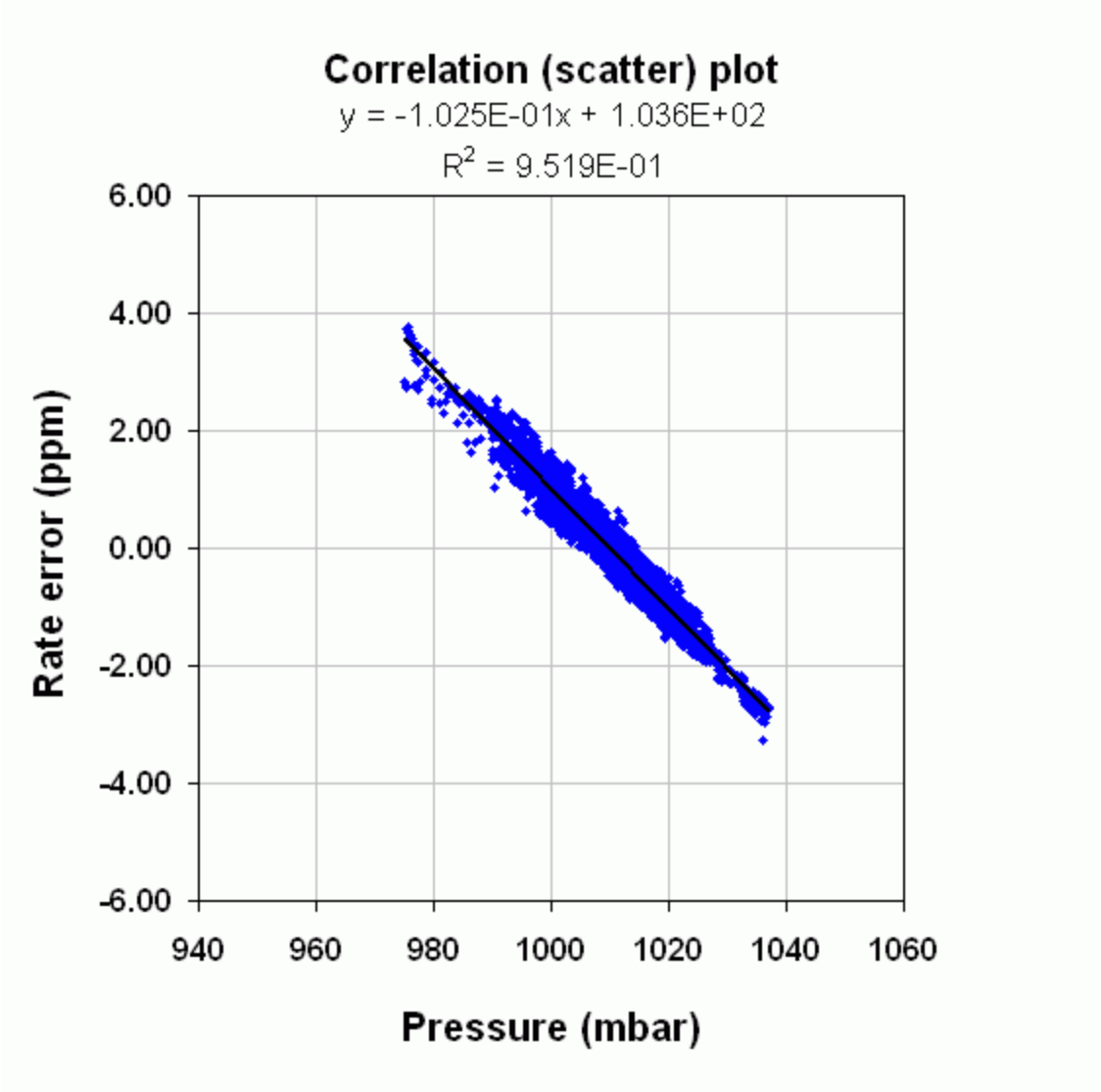
Correlation 6% – temperature



Correlation 0% – humidity



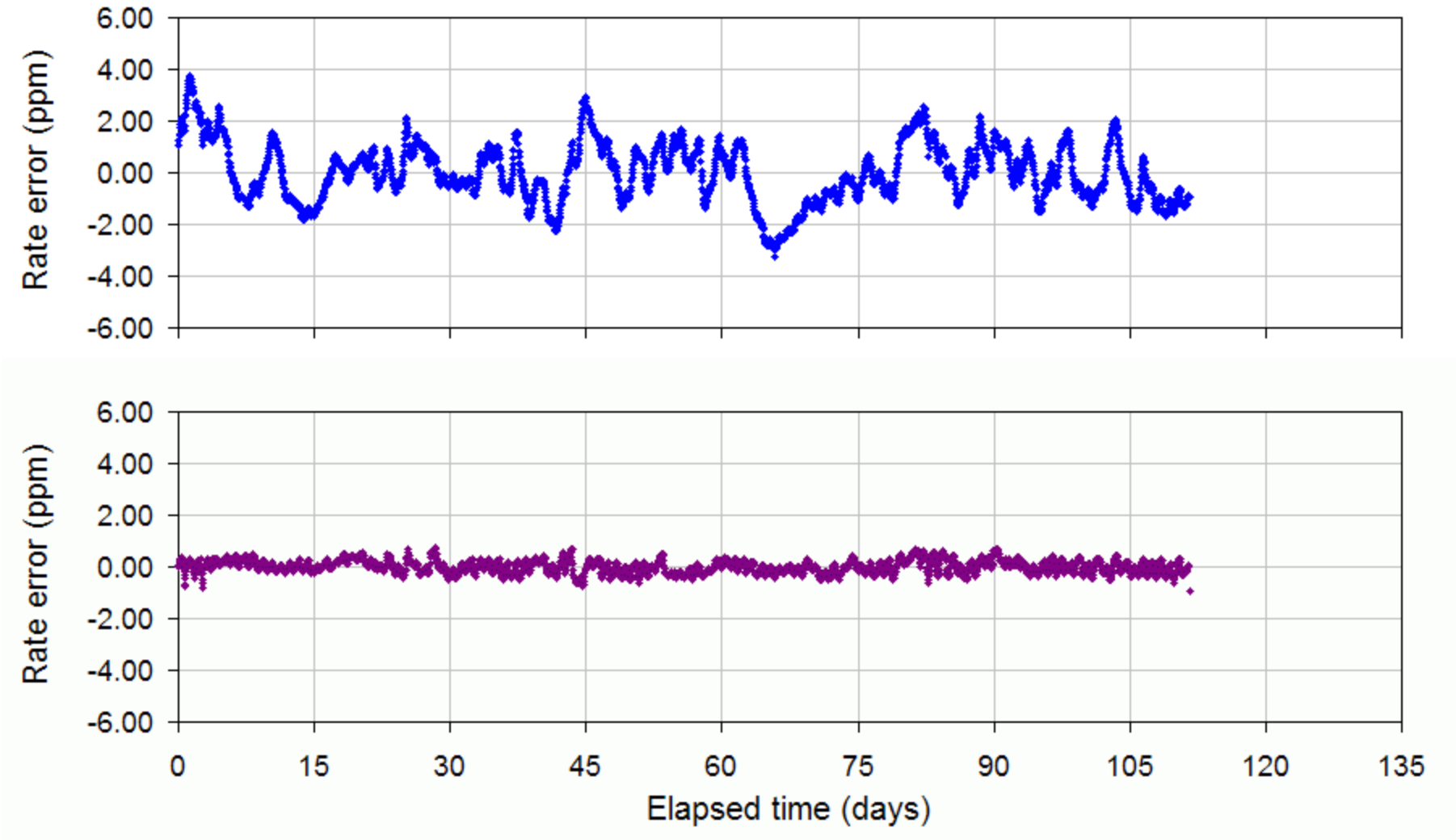
Correlation 95% – pressure



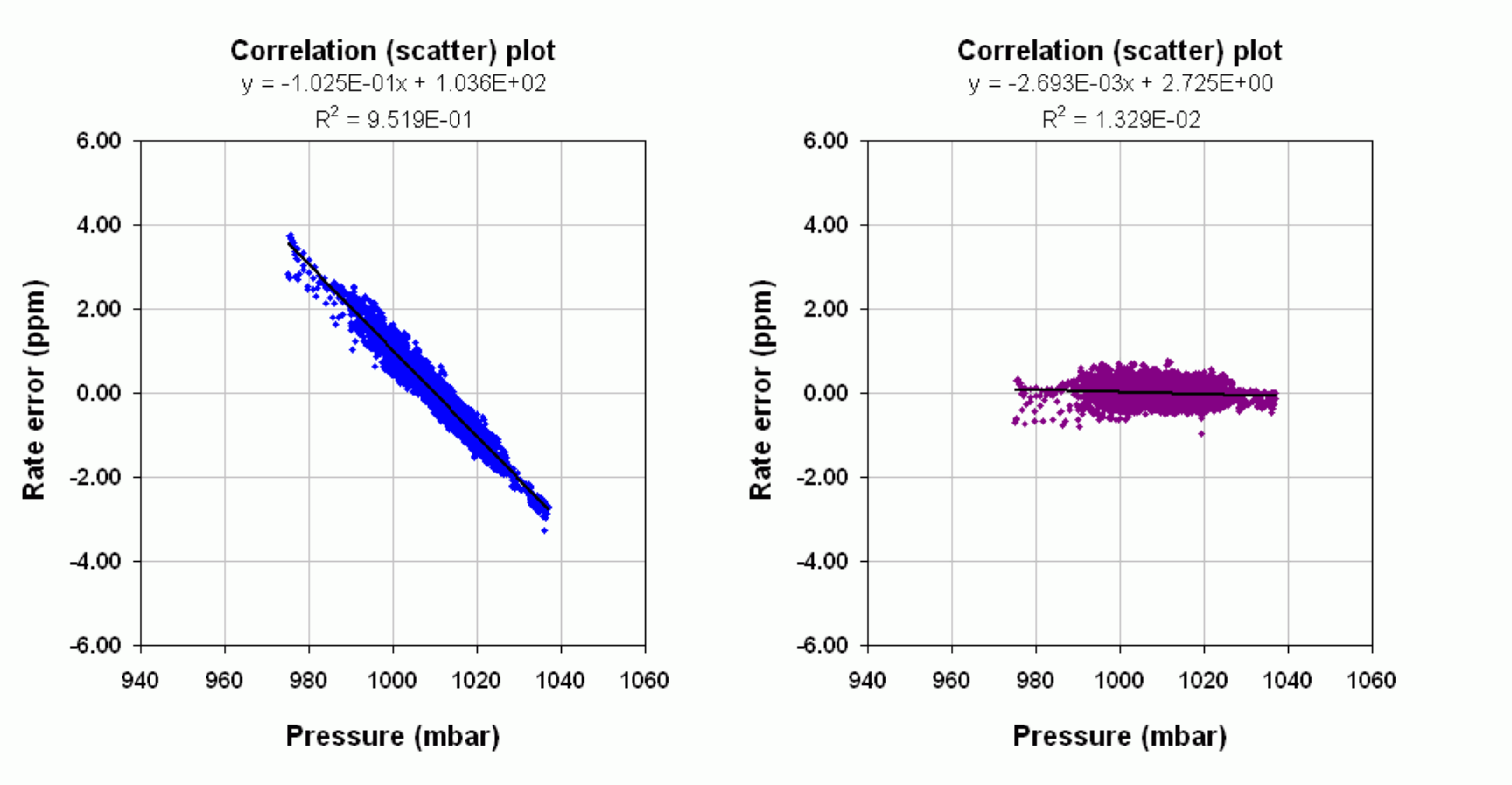
Compensation simulation

- Compute correlation coefficient and then:
  - convert raw time data to (real) rate data
  - compensate rate data in software
  - convert rate data back to (virtual) time data
- Result shows compensation *potential*
- Actual results will be higher
  - real compensation is never perfect

Compensation prediction



Compensation prediction

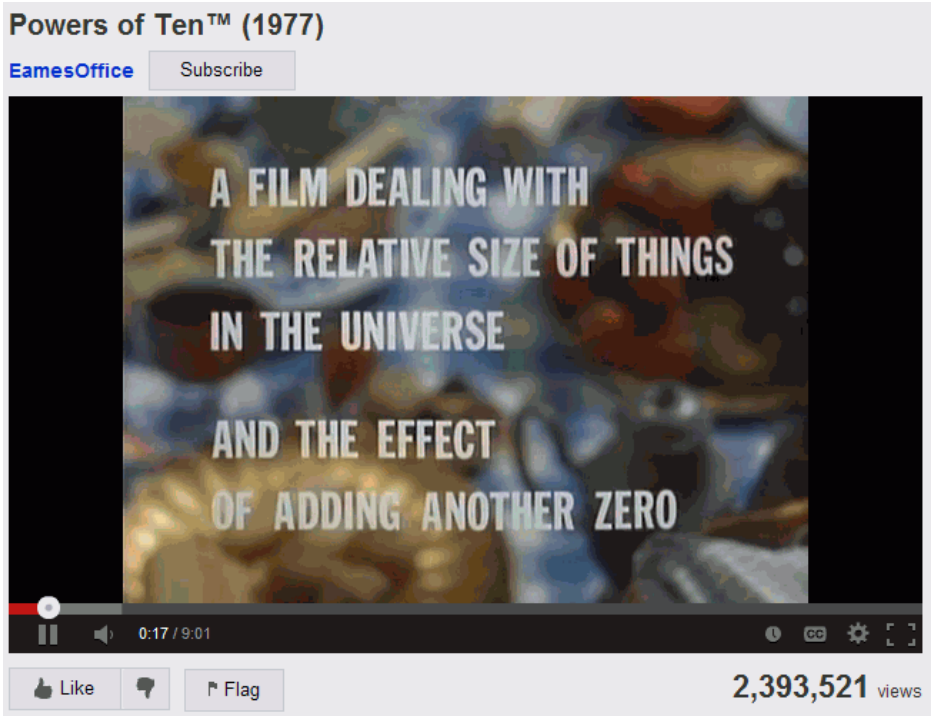


3: In search of the perfect clock

- What is *time*?
  - who knows
- What is *frequency*?
  - repetitive, periodic events
- What is a *clock*?
  - count those periodic events and display
  - anything with consistent period is a clock
  - the more regular, the better the clock

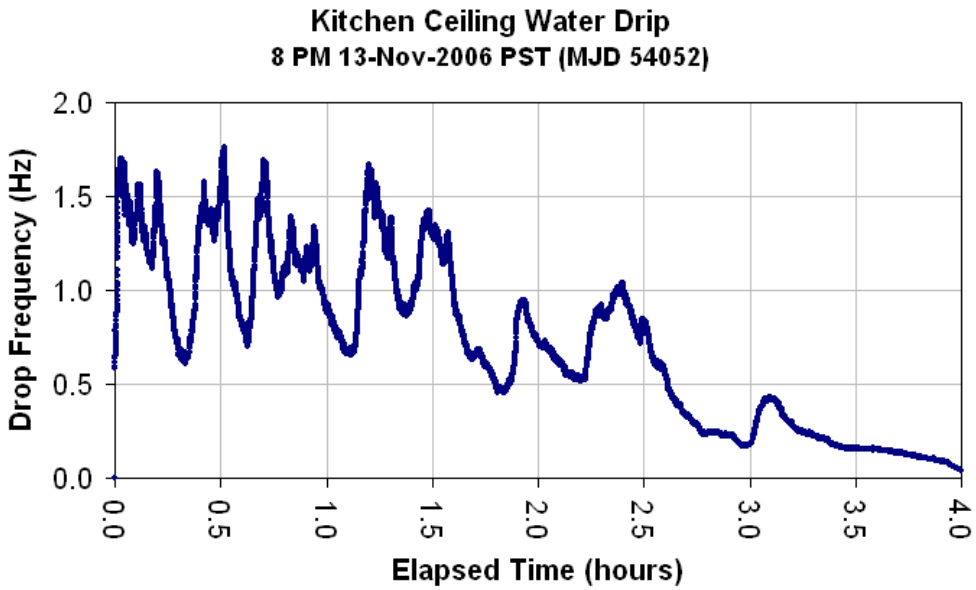
“Powers of Ten” – inspiration

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

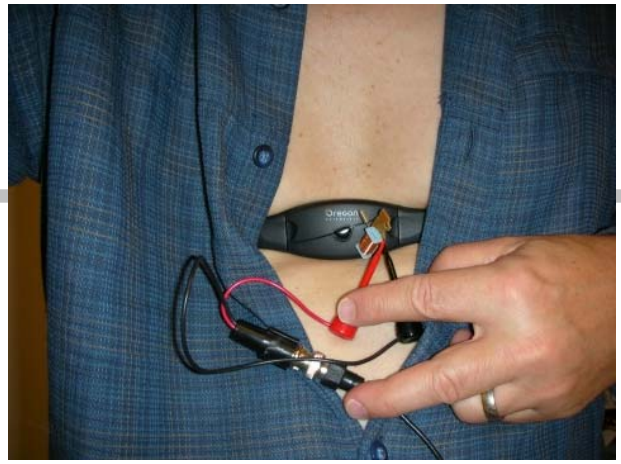


10^{-0} drip, drip

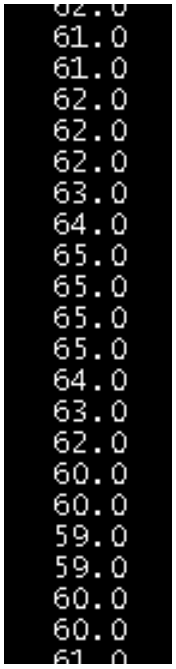
- Leak in ceiling
- 0.57 s … 9.9 s
- 1.7 Hz … 0.1 Hz



10^{-1} heart beat

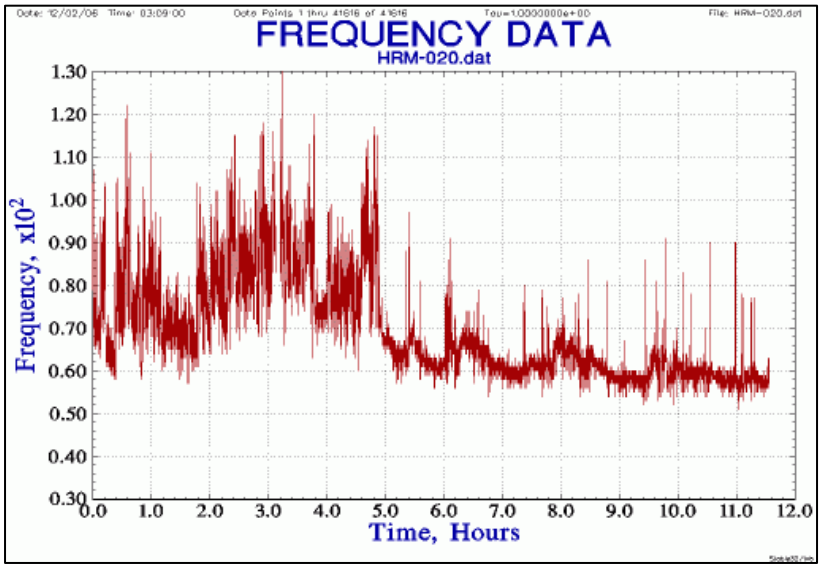


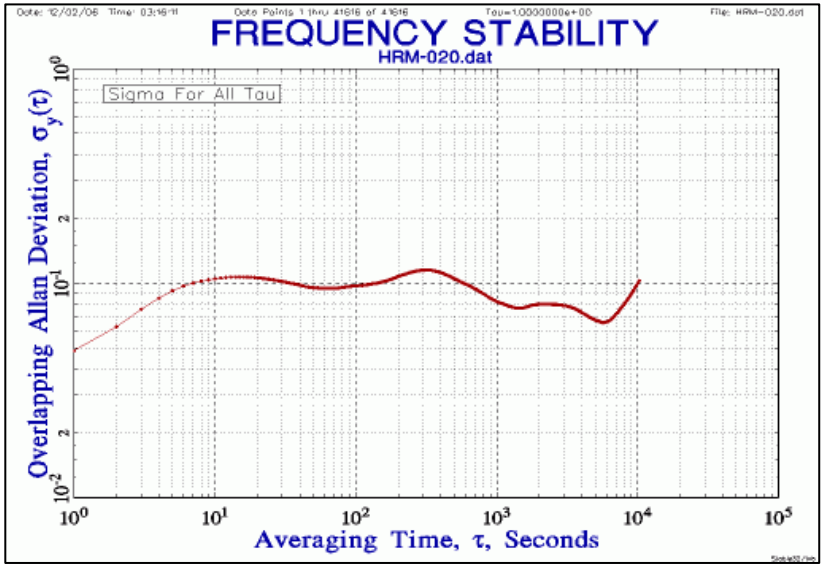
- 10^{-1}, 0.1, 10%
- The original ‘1 PPS’
- Sometimes 2x, even 3x
- Much higher stability at night
- < 10% accuracy possible



10^{-1} heart beat

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



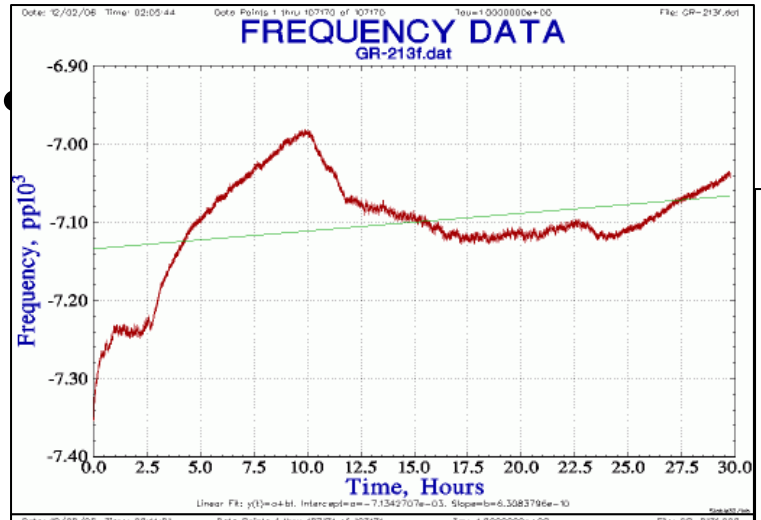


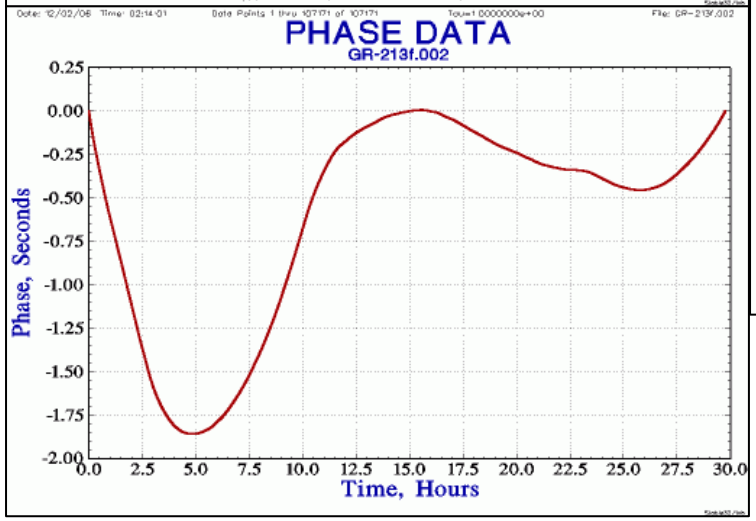
10^{-2} tuning fork oscillator

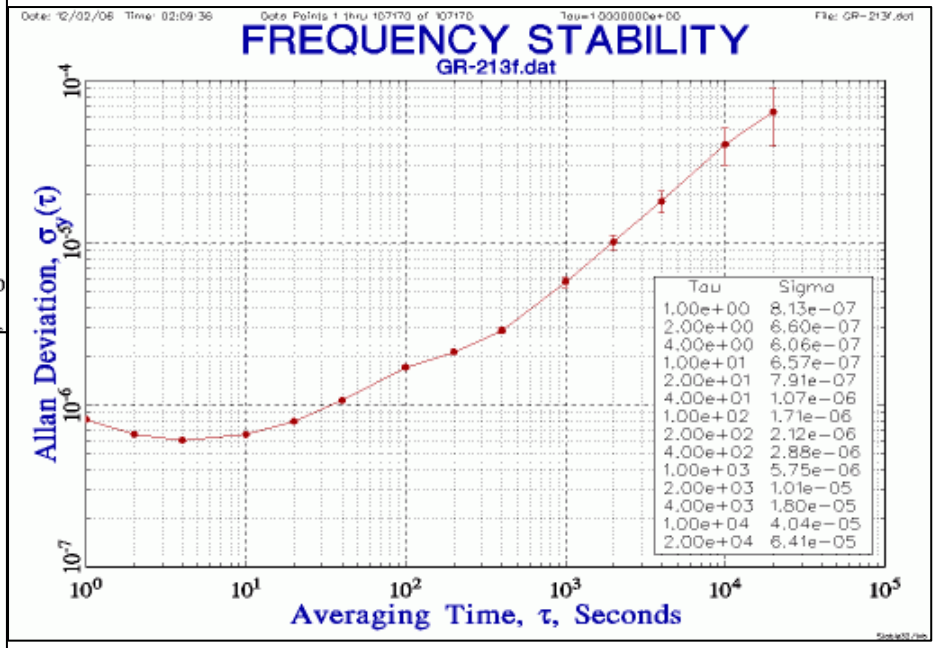
- 0.01, 1%
- General Radio Type 213 Audio Oscillator
- 1 ‘kc’; f = **~992.8** Hz
- ±1.3 mHz (60 x 1 s)
- Accuracy < 1%
- Count those 9’s
- ADEV is 10^{-6}…10^{-4}


```
992.897,388,71 Hz
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

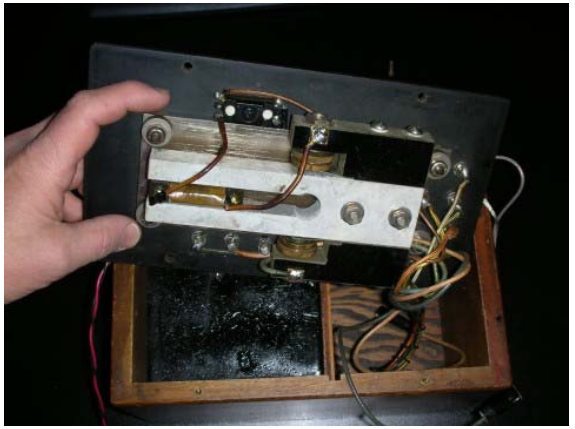


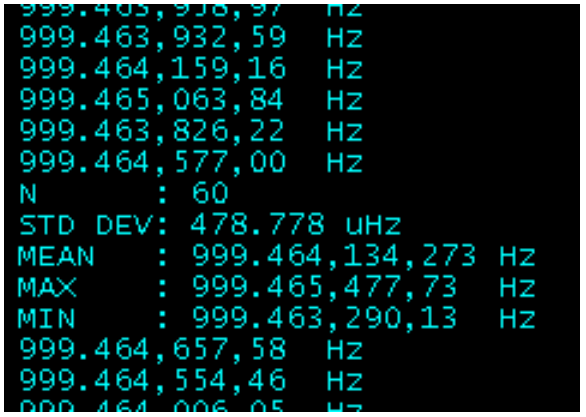




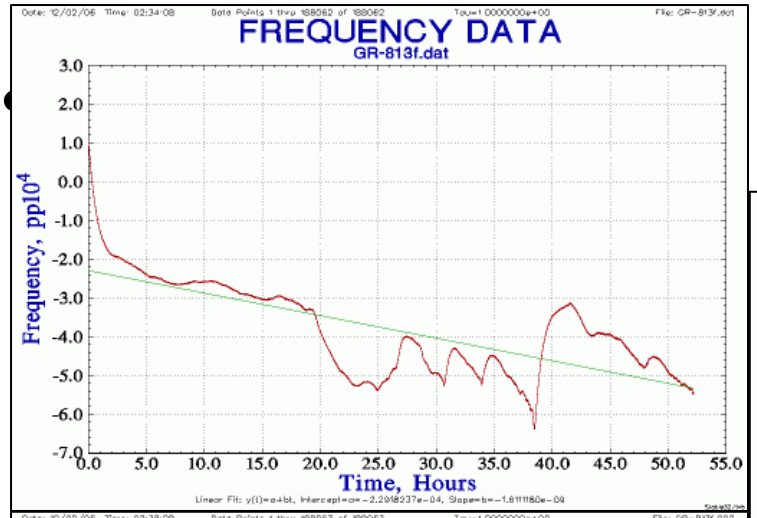
10^{-3} precision tuning fork

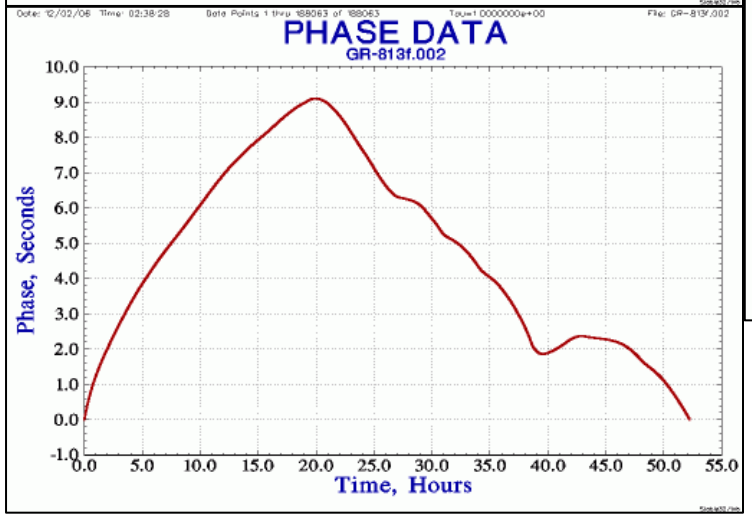
- 0.001, 0.1%, 1 ms/s
- General Radio Type 813 single vacuum tube
- 1 ‘kc’ tuning fork
- f = **~999.4** Hz
- ±400 μHz (60 x 1 s)
- Accuracy < 0.1%
- ADEV is 10^{-7}…10^{-4}

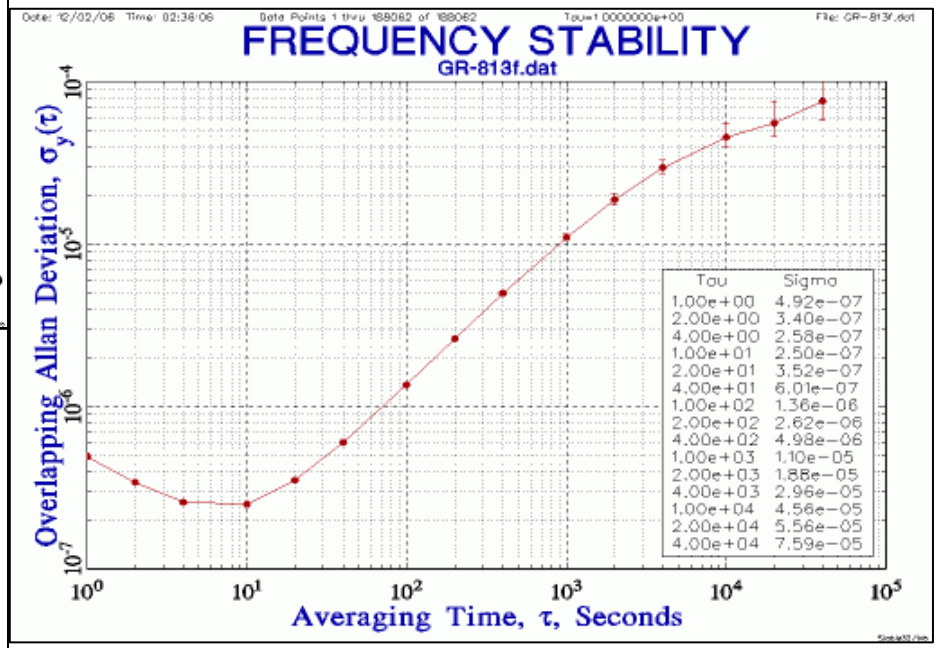




10^{-3} precision tuning fork

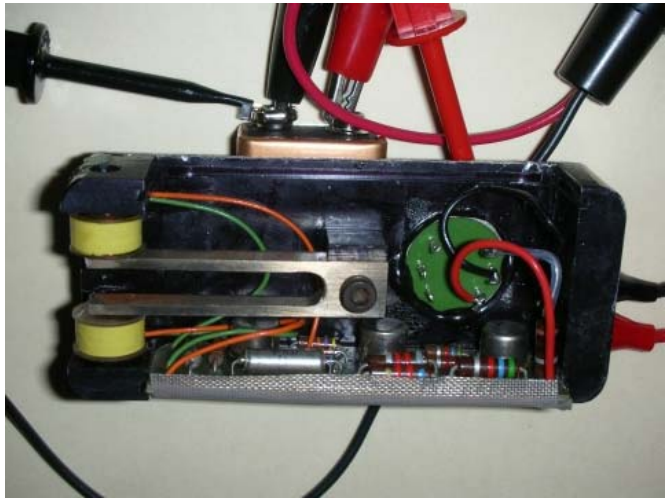






10^{-4} mechanical oscillator

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

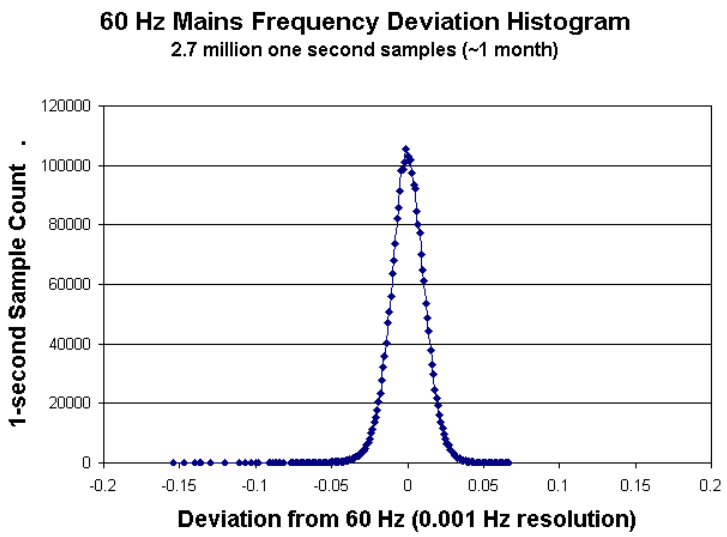


```
999.907,211,67  Hz
999.907,250,33  Hz
999.907,273,16  Hz
999.907,311,01  Hz
999.907,250,27  Hz
999.907,345,09  Hz
N       : 60
STD DEV: 151.812 uHz
MEAN    : 999.907,159,334 Hz
MAX     : 999.907,404,05  Hz
MIN     : 999.906,840,54  Hz
999.907,392,20  Hz
999.907,415,25  Hz
999.907,354,85  Hz
```

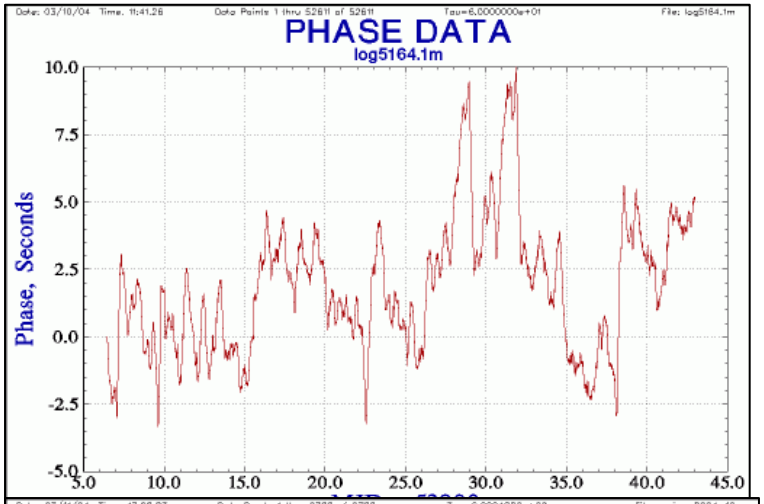
10^{-5} mains (line frequency)

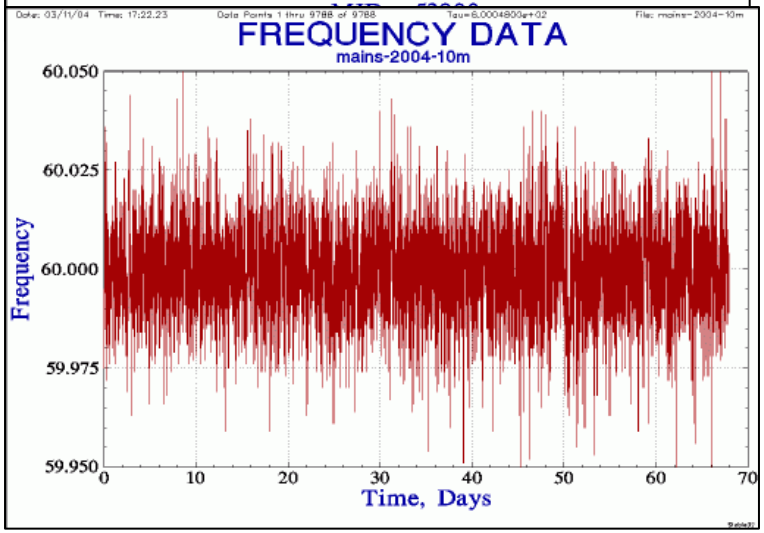
- 0.001%, 10 ppm
- 60± Hz

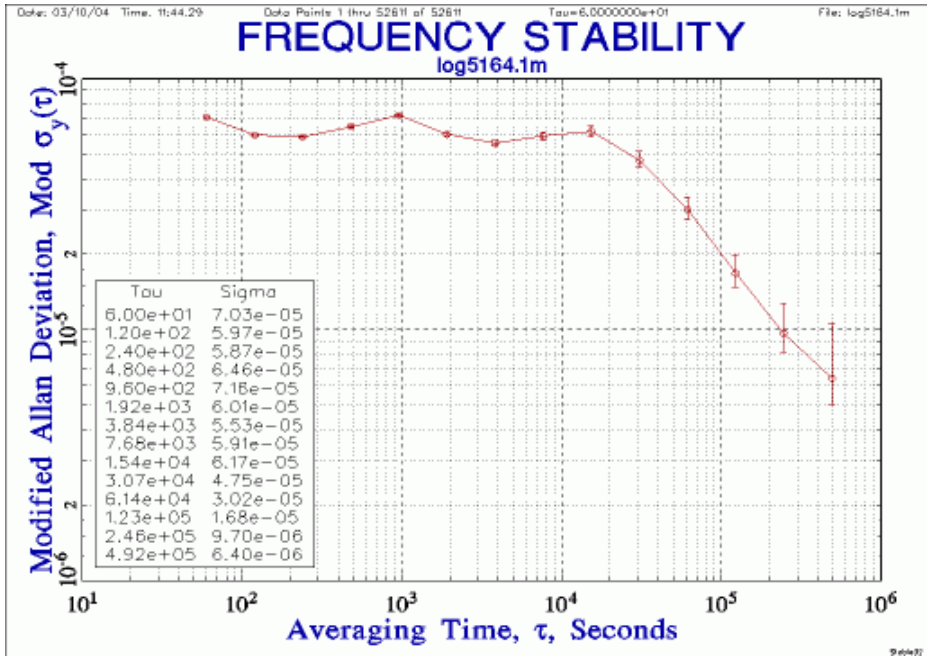
```
60.003,640,120,5  Hz
60.009,491,393,8  Hz
60.000,431,181,6  Hz
59.992,198,219,9  Hz
59.987,371,509,5  Hz
59.993,148,200,6  Hz
59.999,032,462,5  Hz
59.985,892,634,1  Hz
59.995,727,396,2  Hz
N       : 36
STD DEV: 0.006,765,596,40 Hz
MEAN    : 59.999,554,563,23 Hz
MAX     : 60.010,390,980,5  Hz
MIN     : 59.985,892,634,1  Hz
59.996,011,518,6  Hz
```



10^{-5} mains (line frequency)

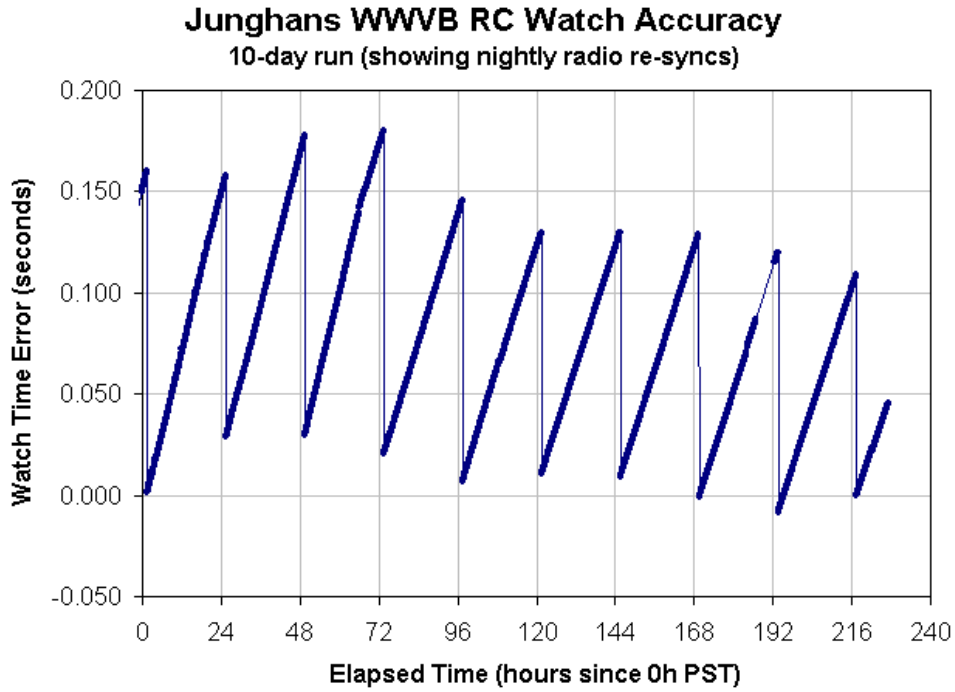






10^{-6} quartz watch (RC)

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

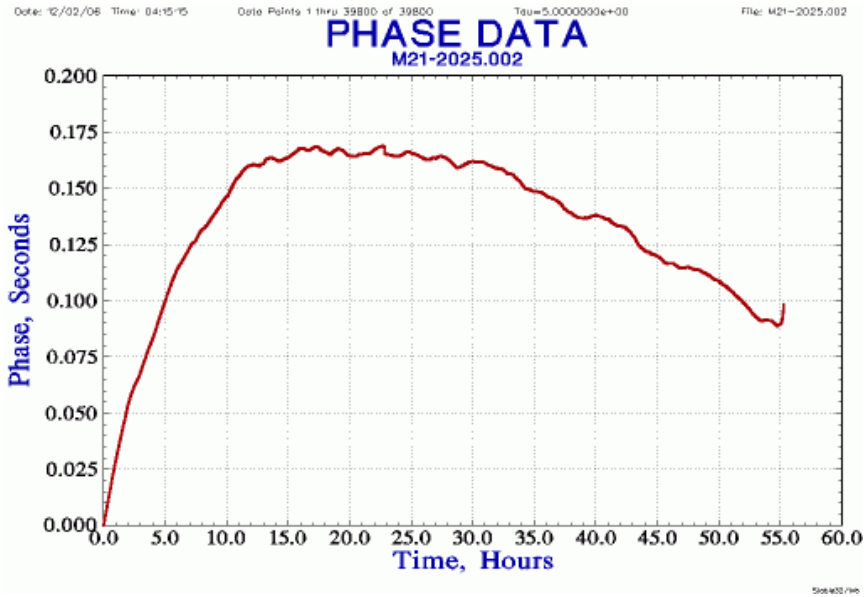


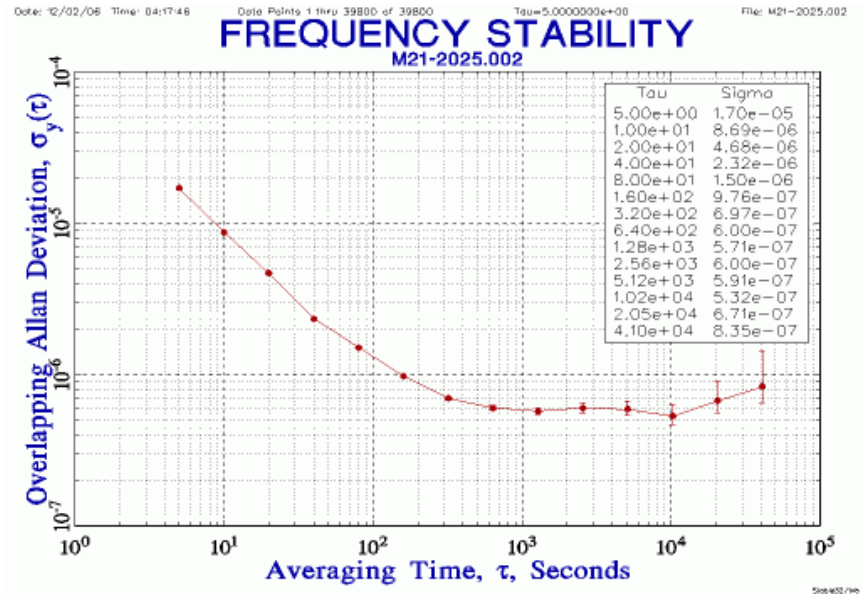
10^{-7} chronometer

- 0.1 ppm
- Rated ¼ sec/day deviation

10^{-7} chronometer

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

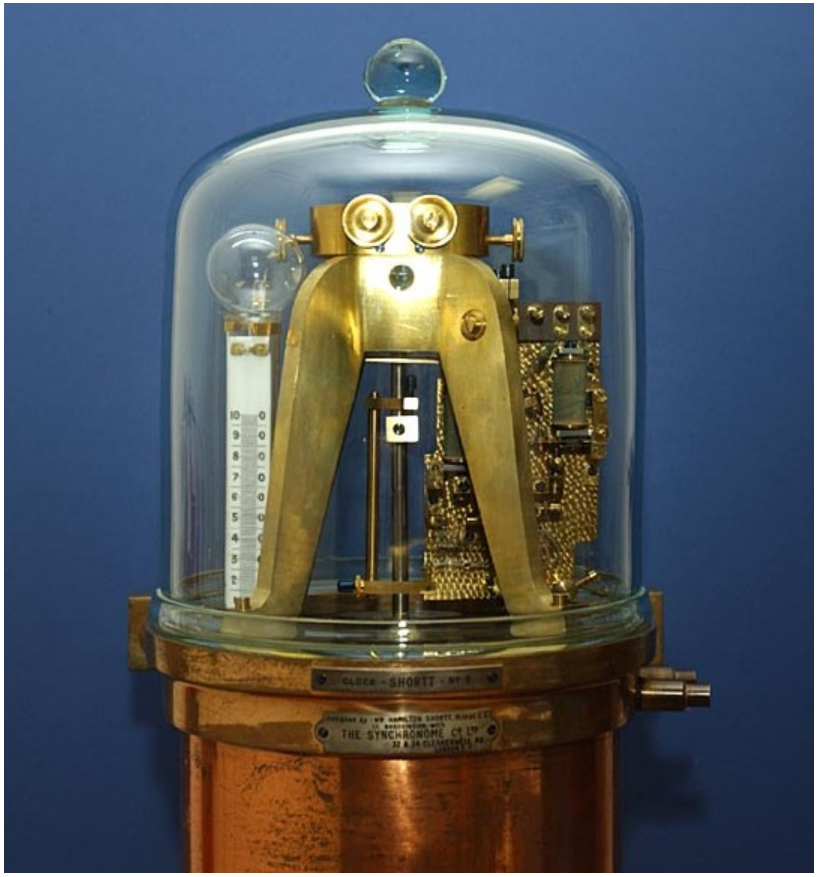




10^{-8} pendulum clock

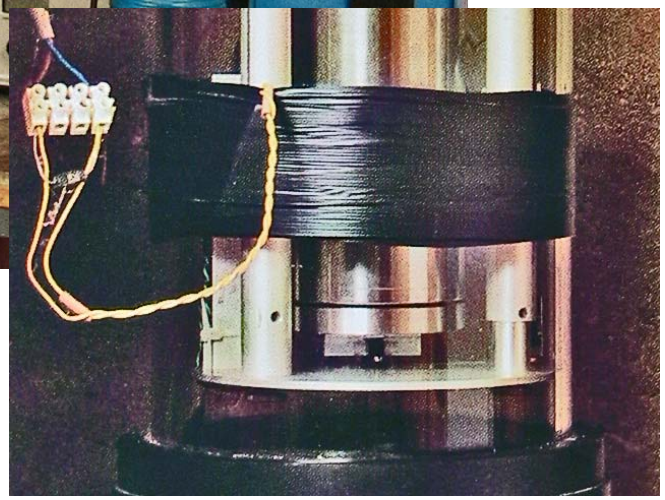
- 0.01 ppm, 10 ppb
  10 ns/s, 864 μs/d
- Shortt,
  Fedchenko,
  Riefler,
  ‘Littlemore’

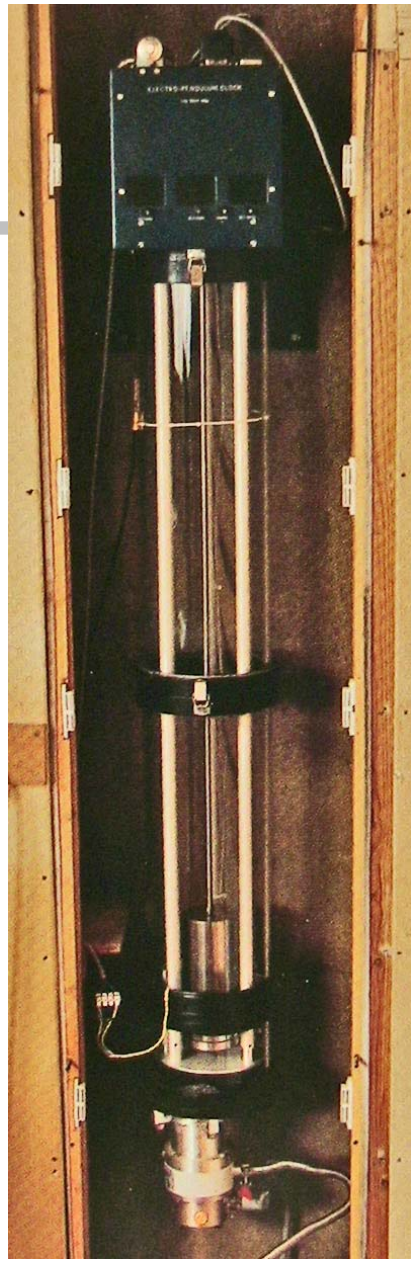
Shortt-Synchronome



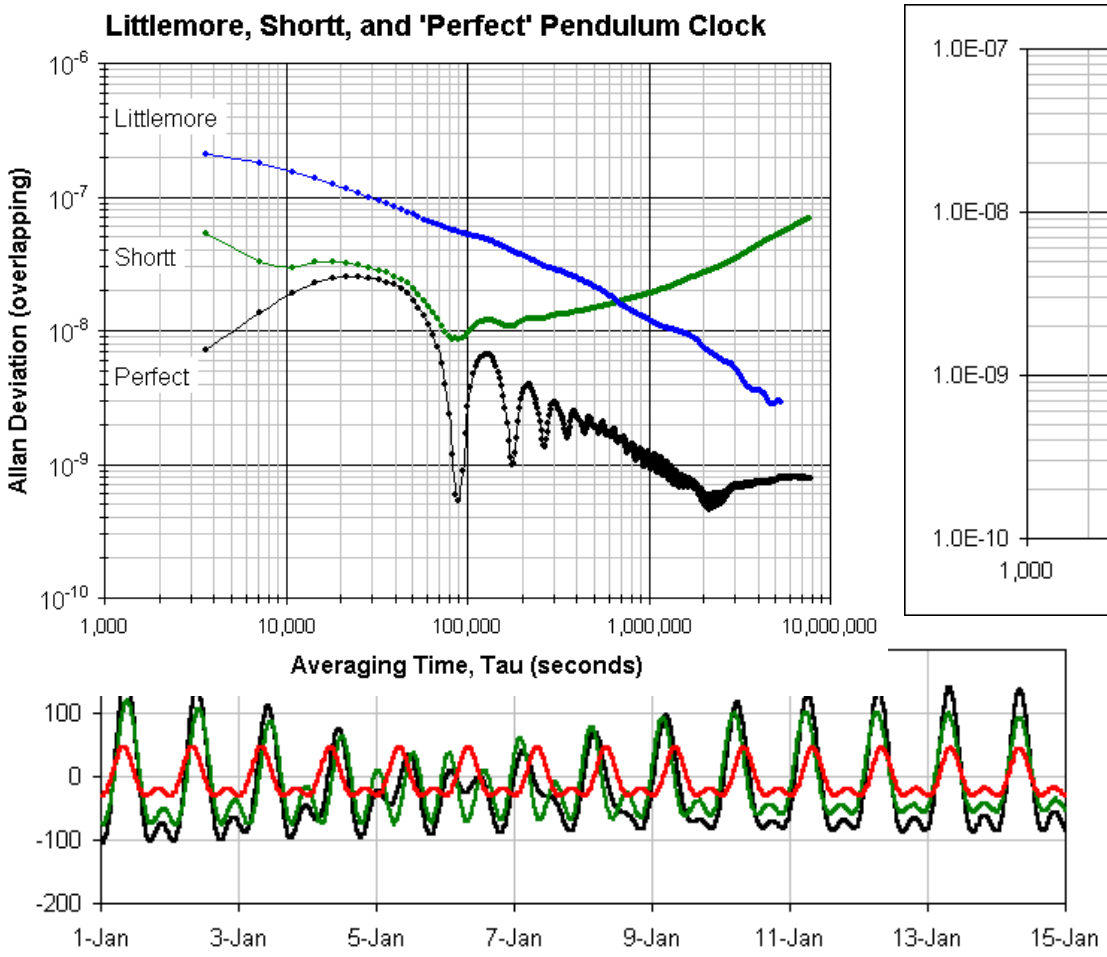
Fedchenko AChF-3

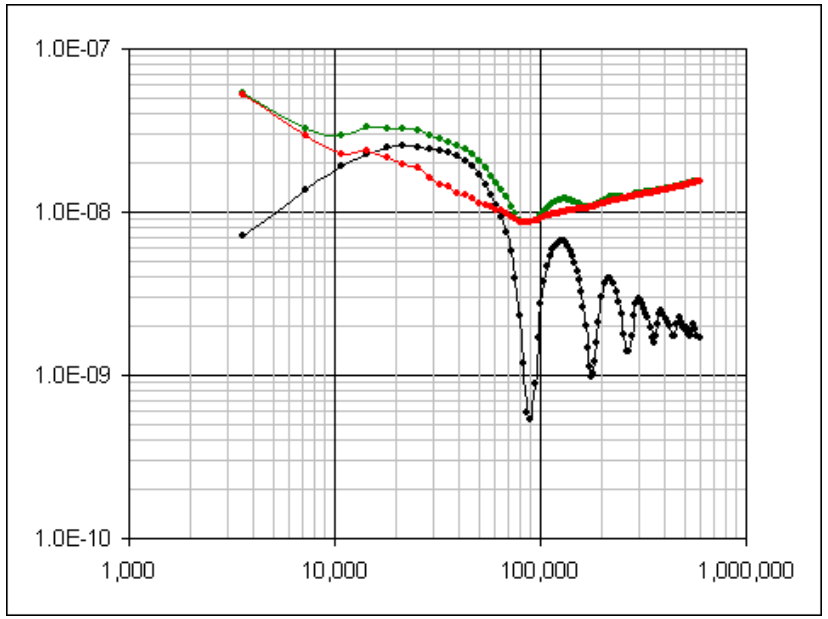
Littlemore clock





10^{-8} pendulum clock

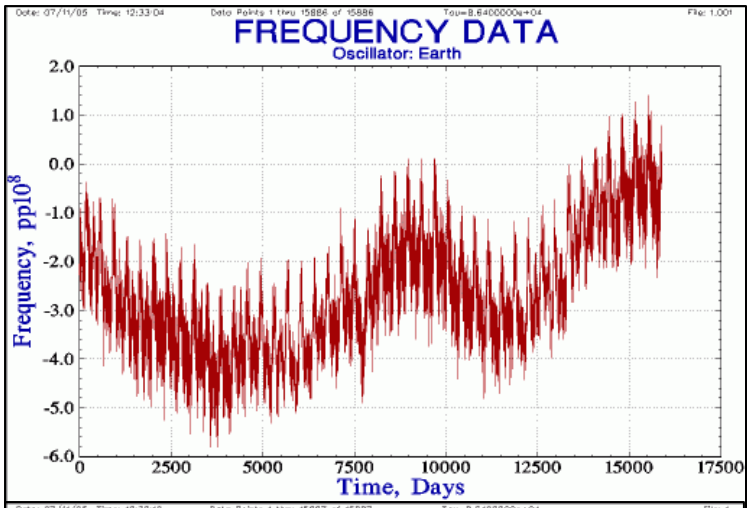


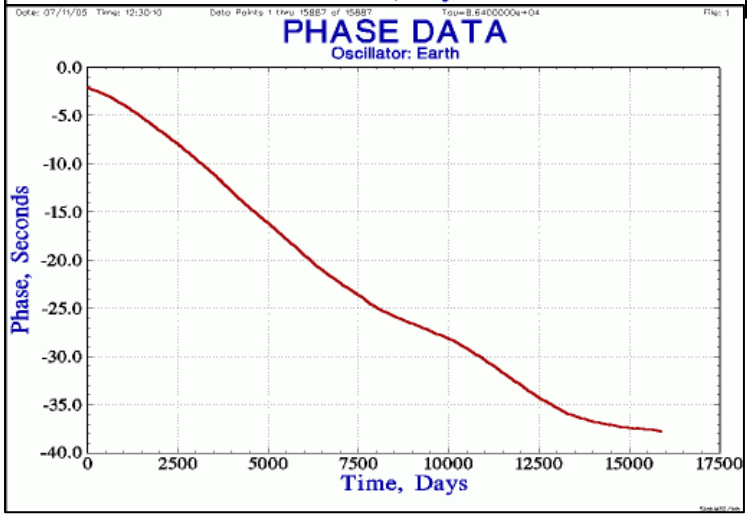


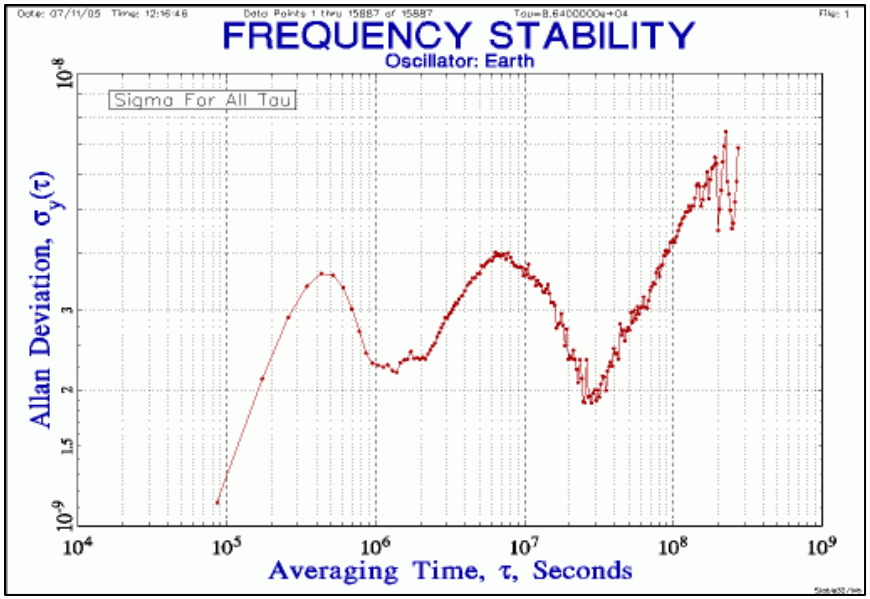
10^{-9} earth

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

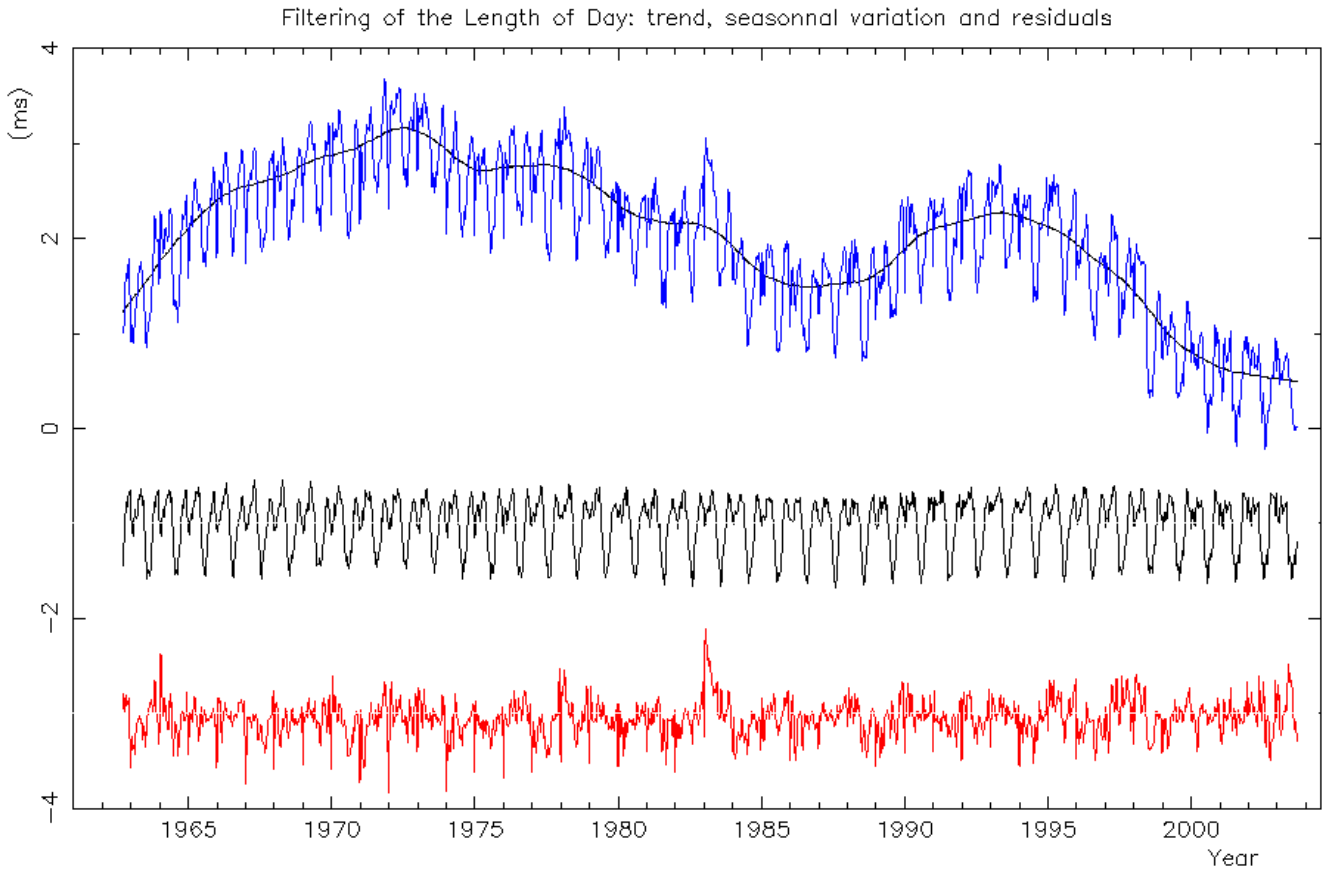
10^{-9} earth (40y of data)







10^{-9} earth clock

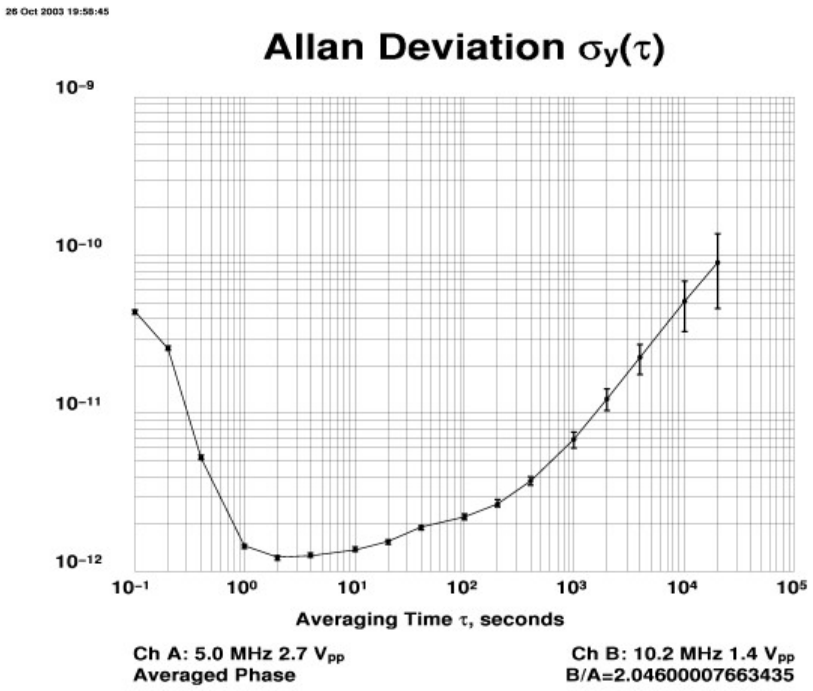


10^{-9} earth frequency standard

- 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

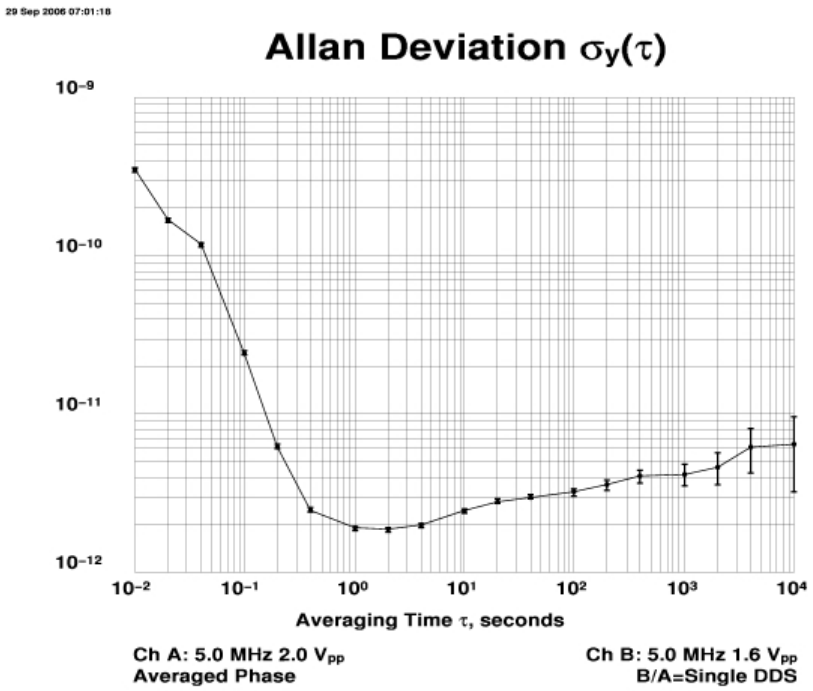
- 0.1 ppb, 100 ps/s, 8.64 µs/d
- 10^{-10}…10^{-13} short
- 5×10^{-10}/d drift



c:\tvb\Tscplot\Log4165.gif

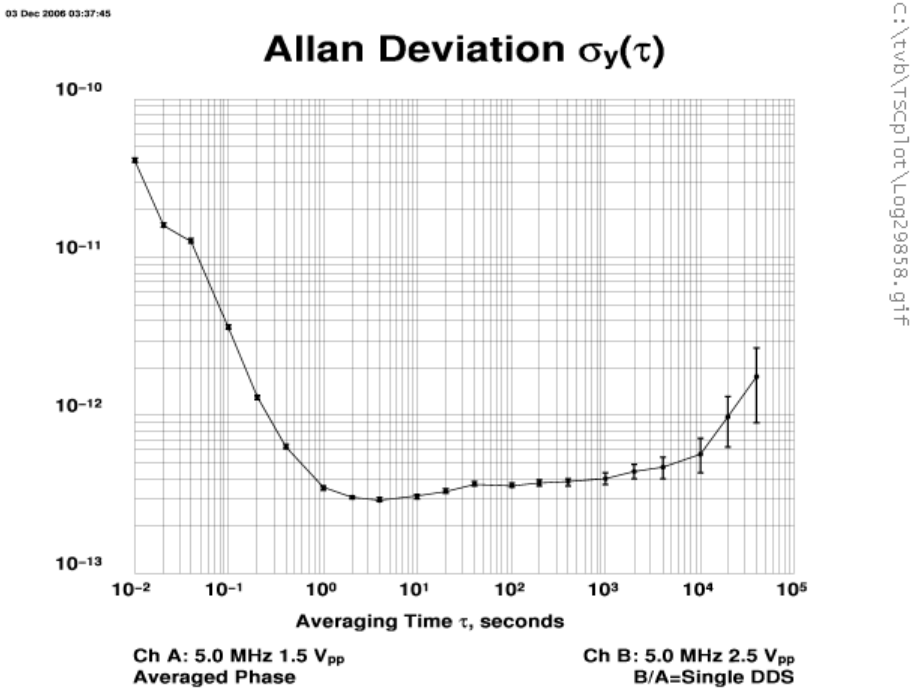
10^{-11} good ocxo

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



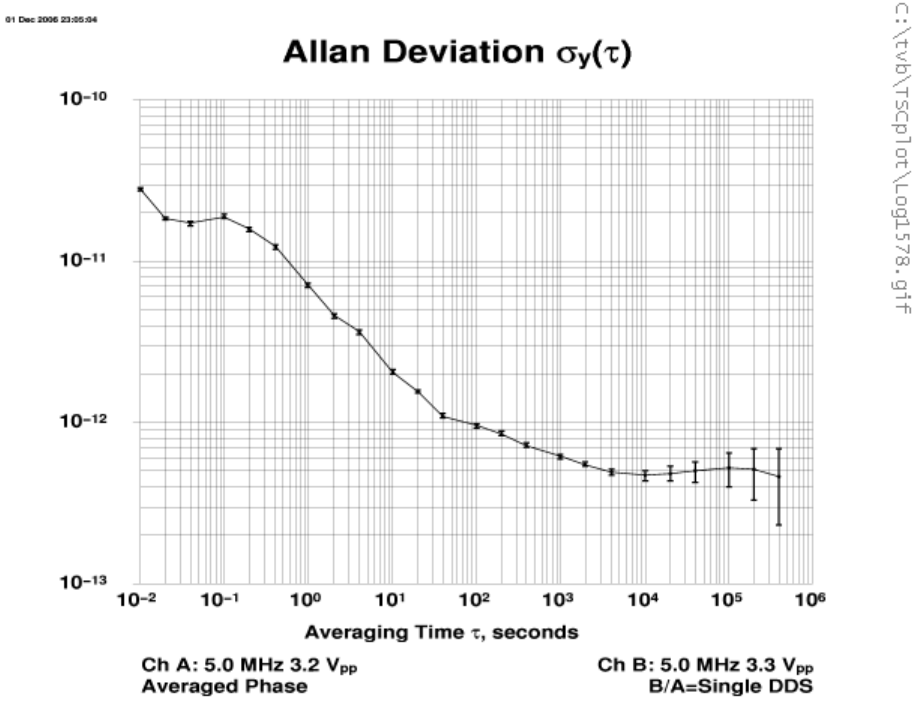
10^{-12} excellent ocxo

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



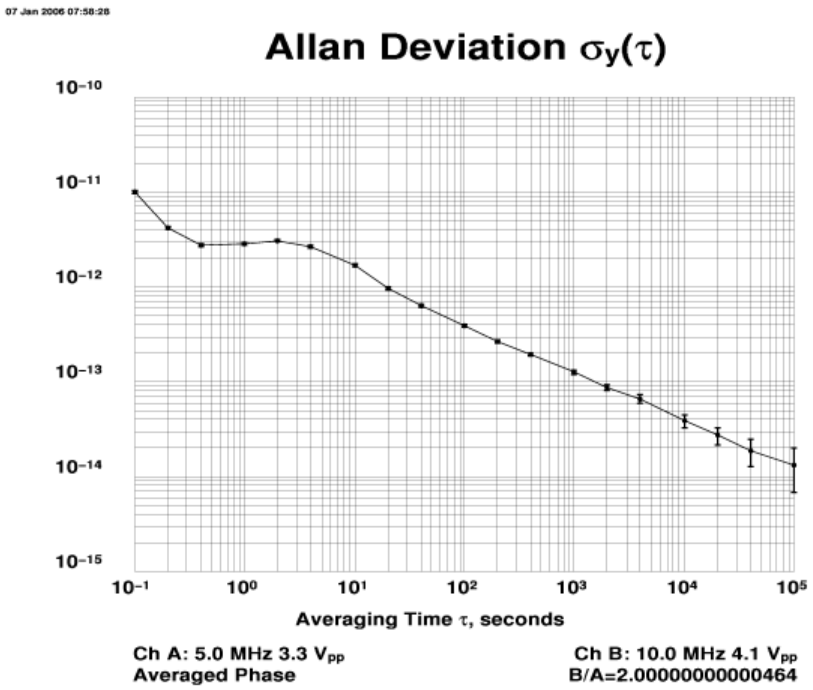
10^{-13} rubidium

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



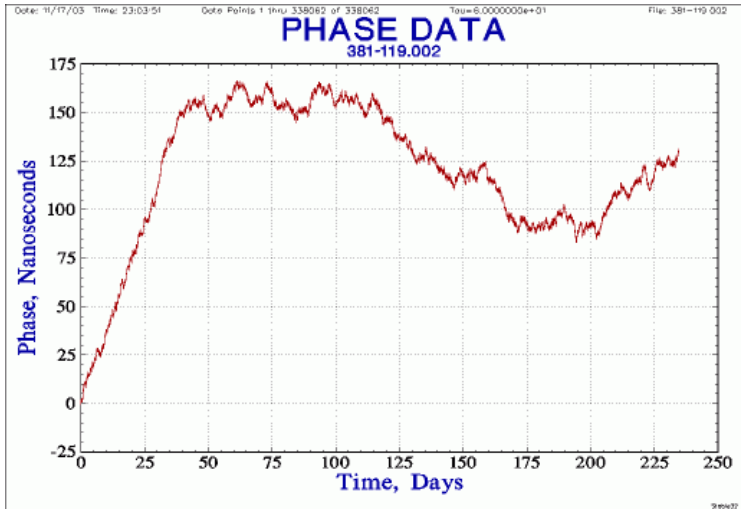
10^{-14} cesium

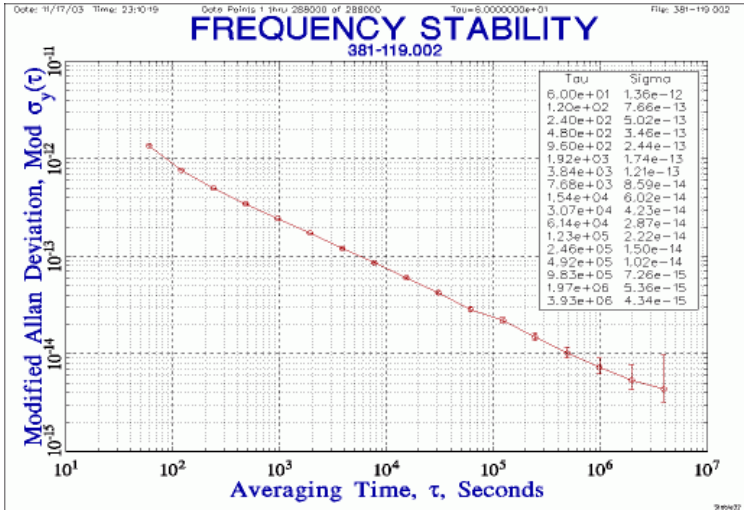
- 864 ps/d (~1 ns/d)
- ~10^{-13} mid-term
- ~1×10^{-14} @ 1 day



10^{-15} hp 5071A cesium

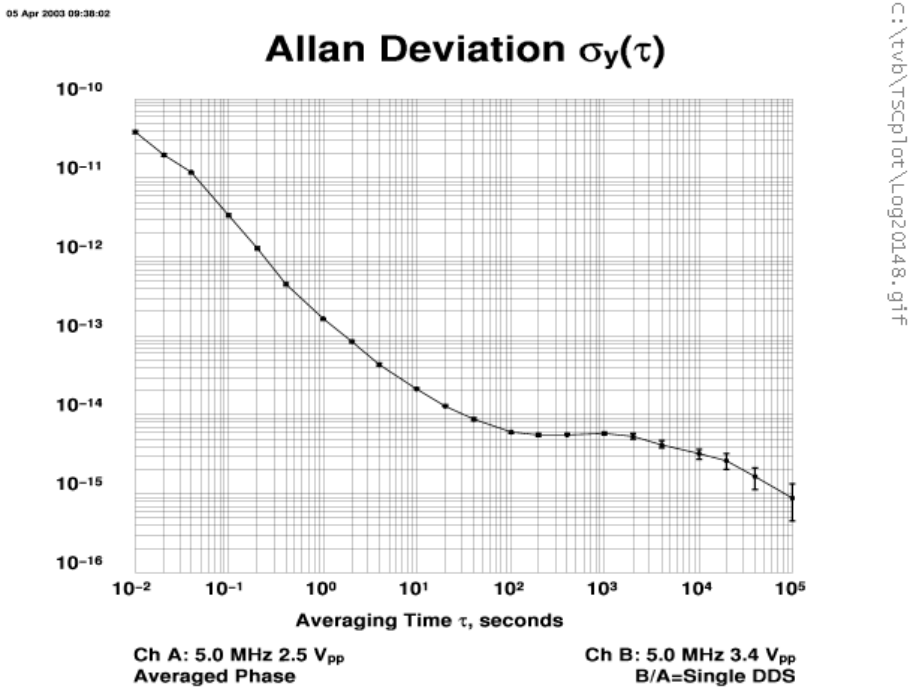
- High-performance model
- Pair ~2×10^{-14} at a day
- Flicker floor ~5×10^{-15} in weeks





10^{-16} active h-maser

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



c:\tvb\Tsplot\Log20148.gif

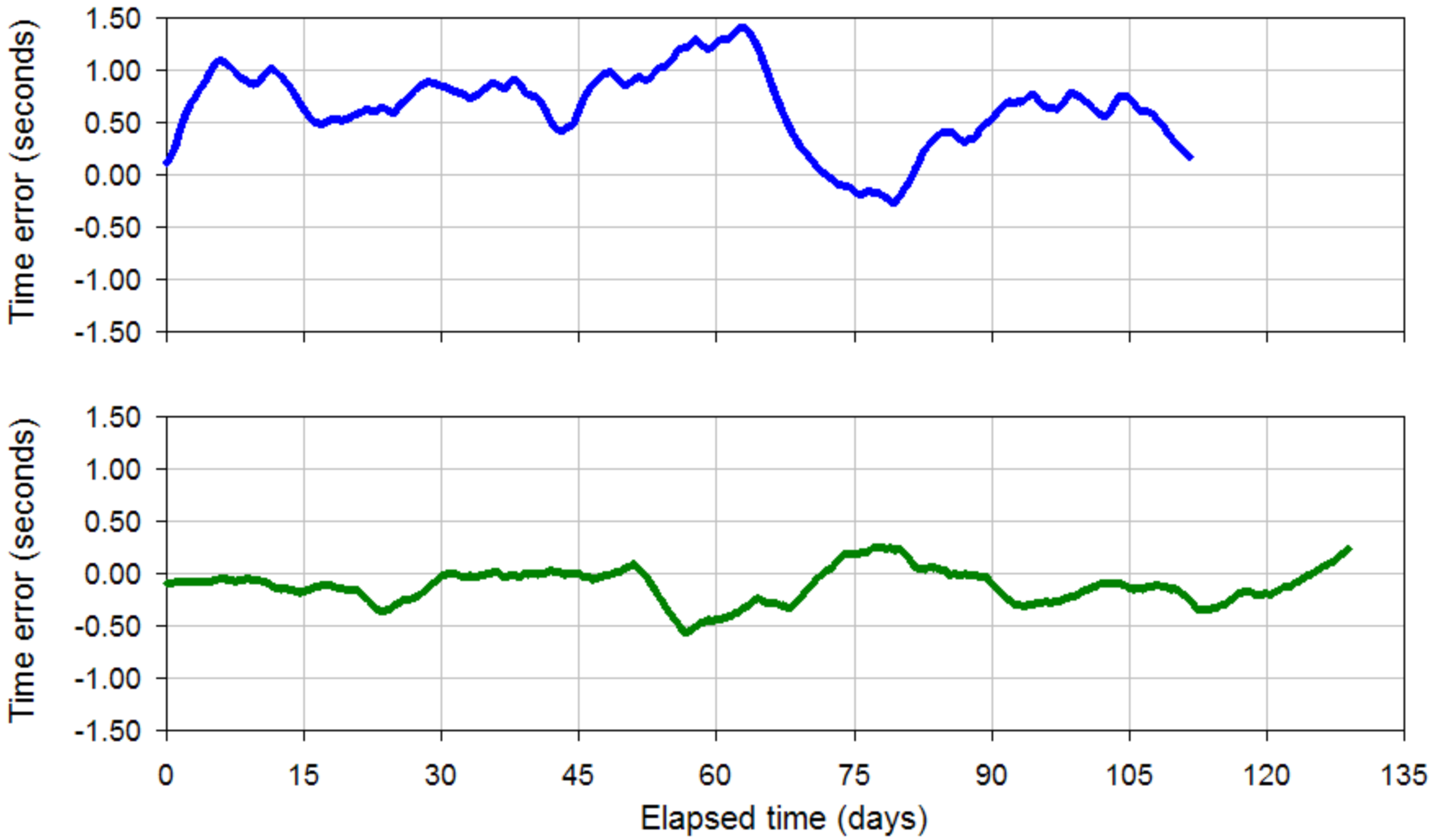
Summary – powers of ten

- 17 orders of magnitude
- Earth and pendulum clocks in the middle
- Even atomic clocks are not perfect

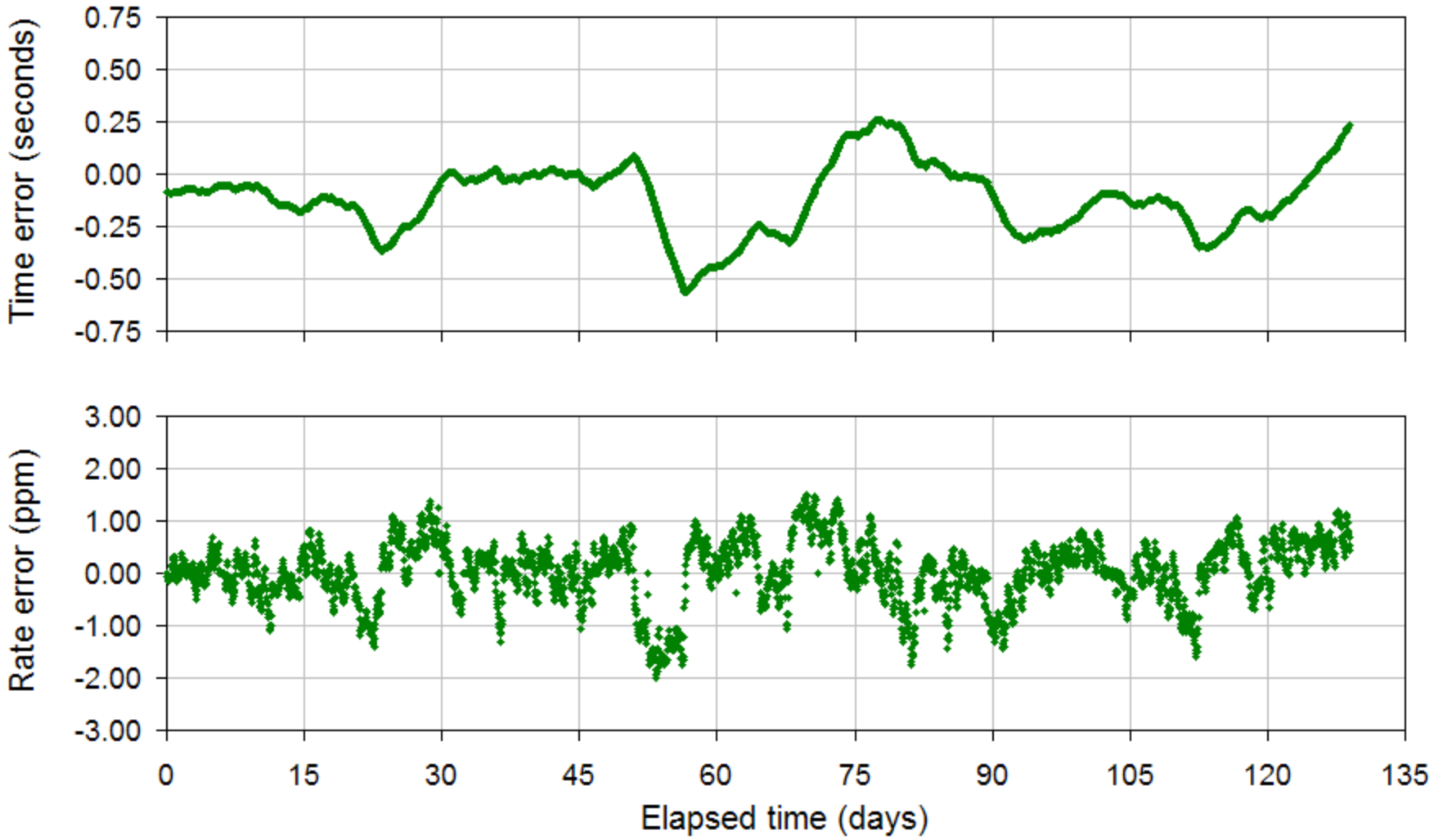
4: Second look, Clock “B”, 2015

- Now called “Clock B”
- Raw Microset / GPS data files
  - 300 second (5 min) samples
  - December 1, 2014 to April 8, 2015
  - 129 days
- N.B. all 2014/2015 plots in **green**

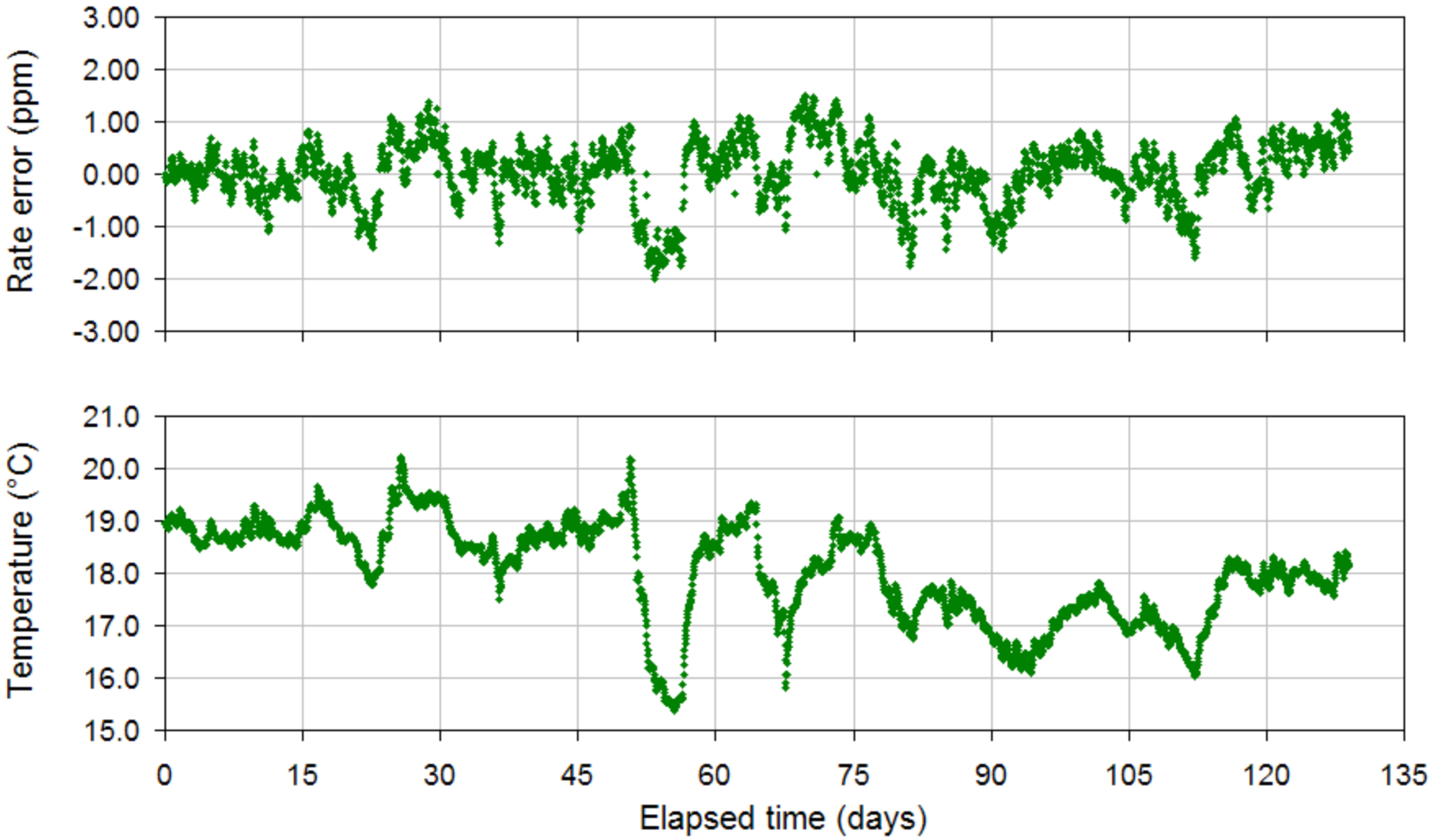
2013 data vs. 2015 data



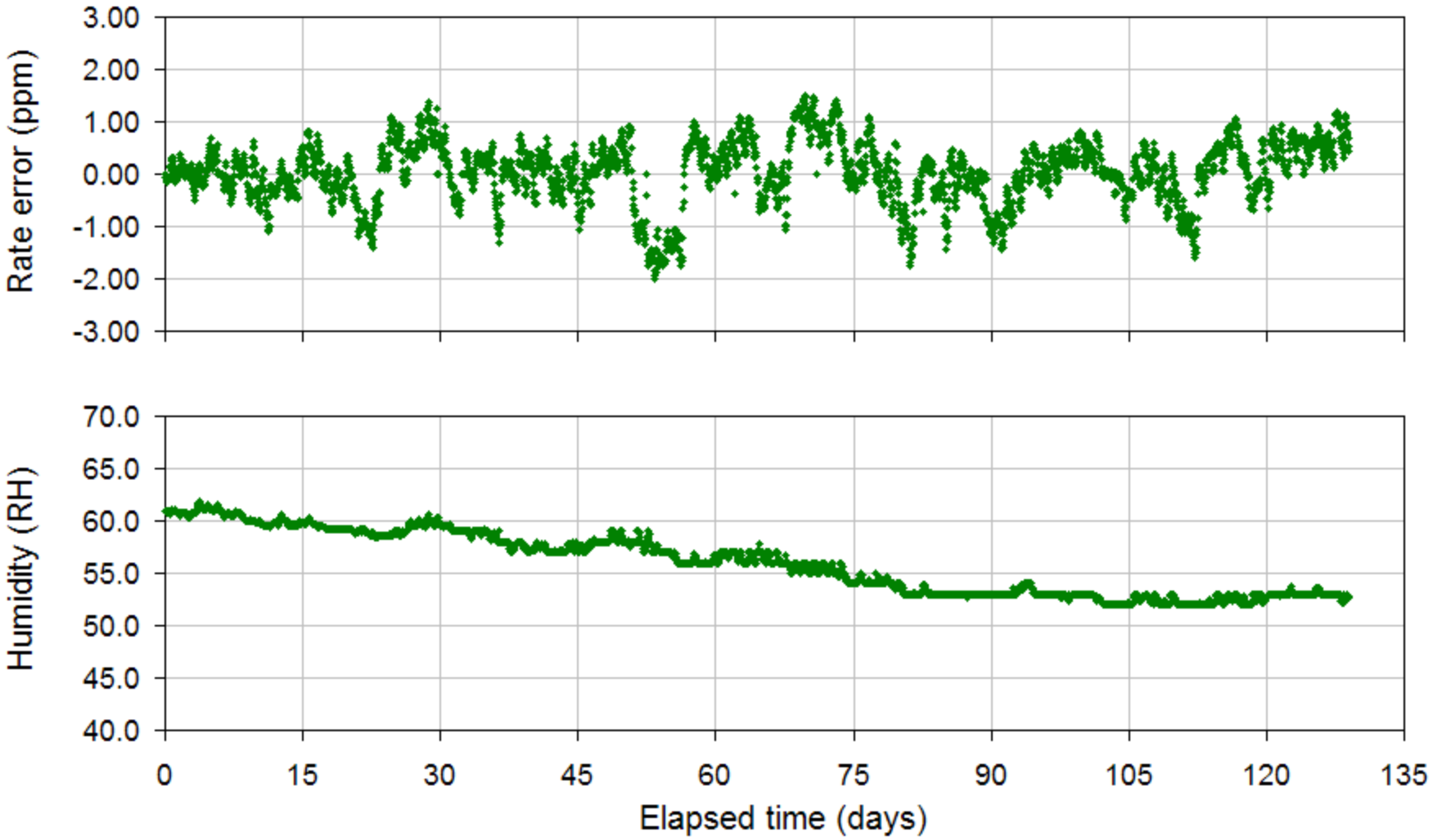
Time drift and rate error (ppm)



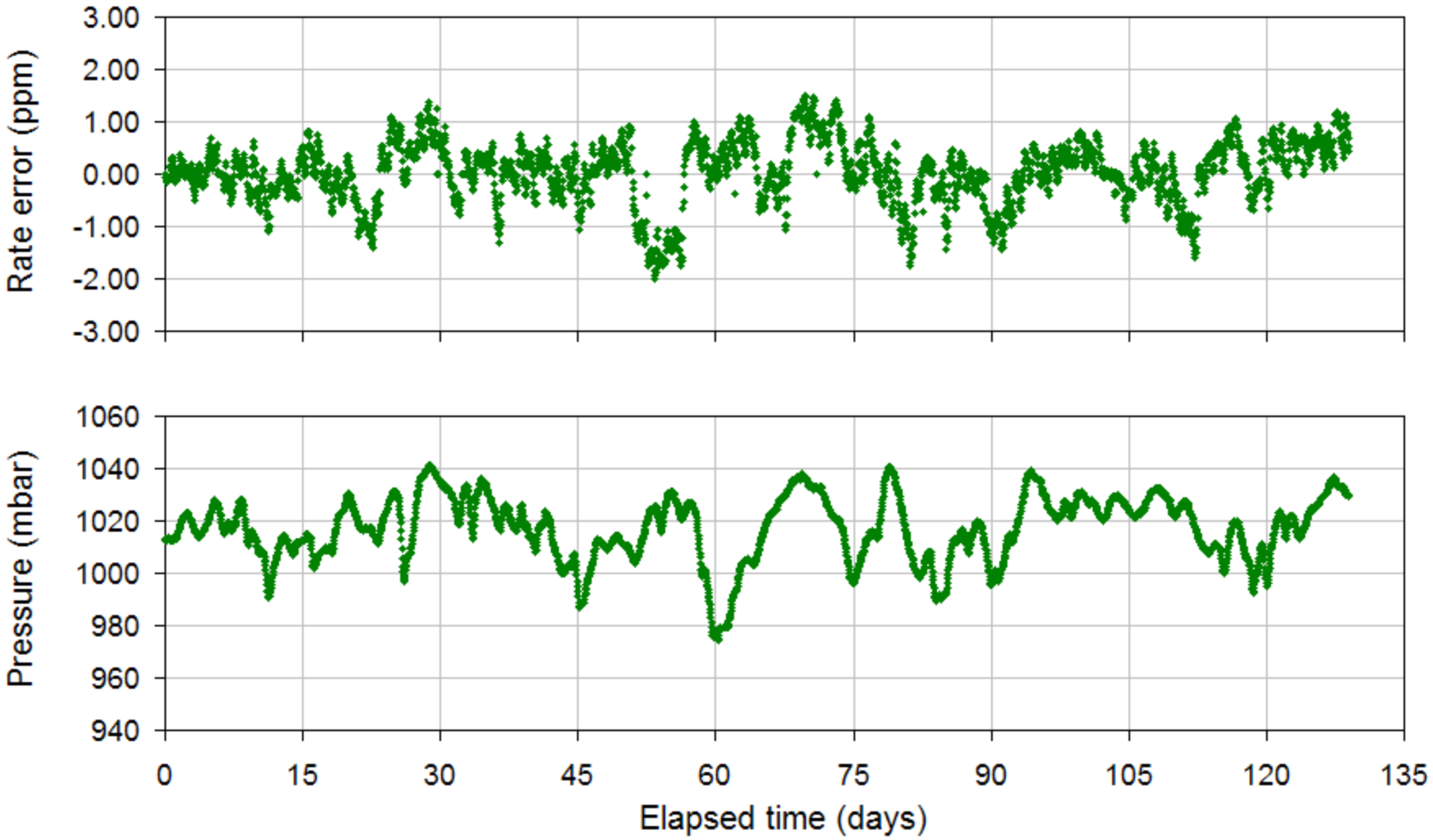
1) rate vs. temperature



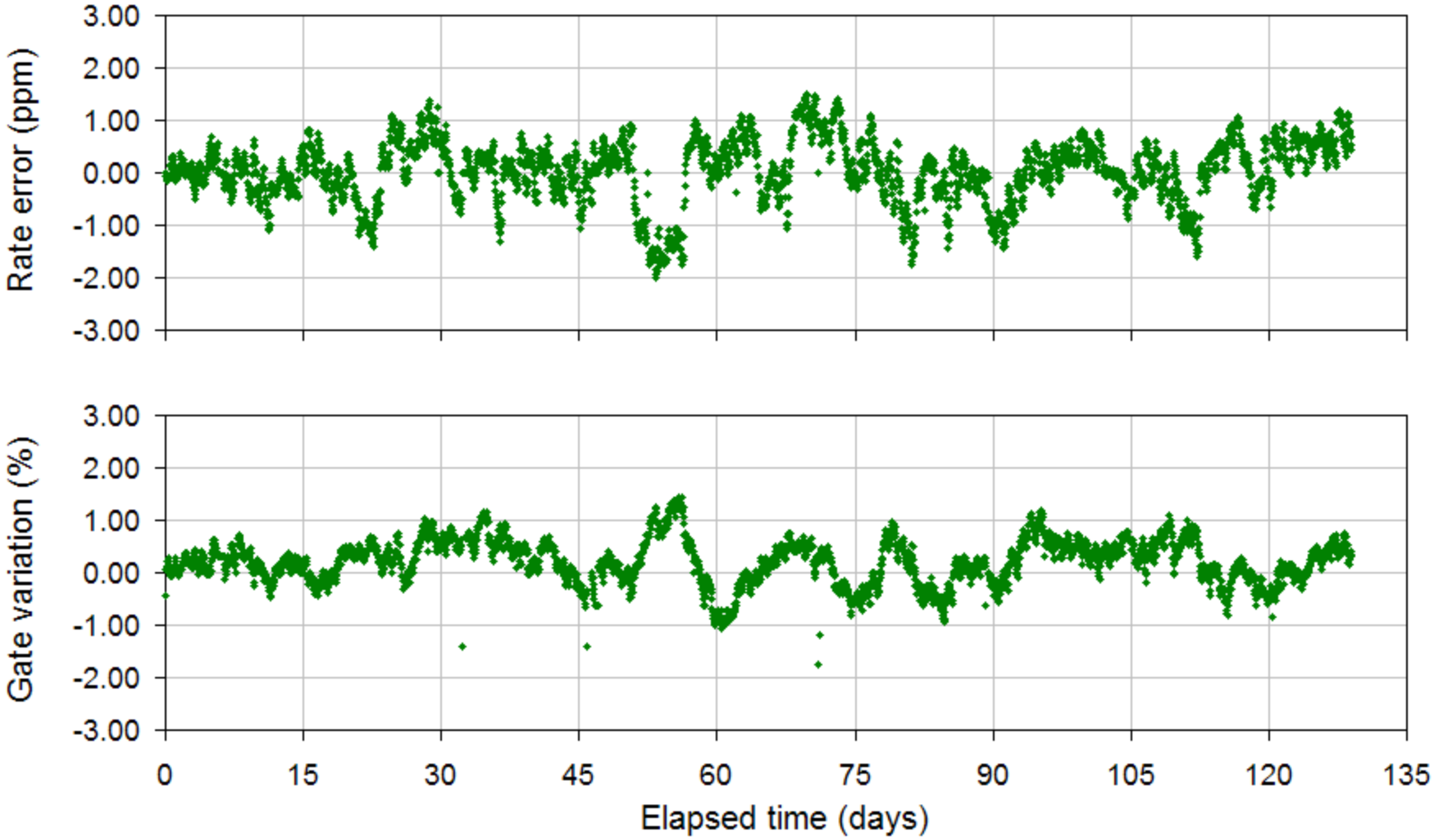
2) rate vs. humidity



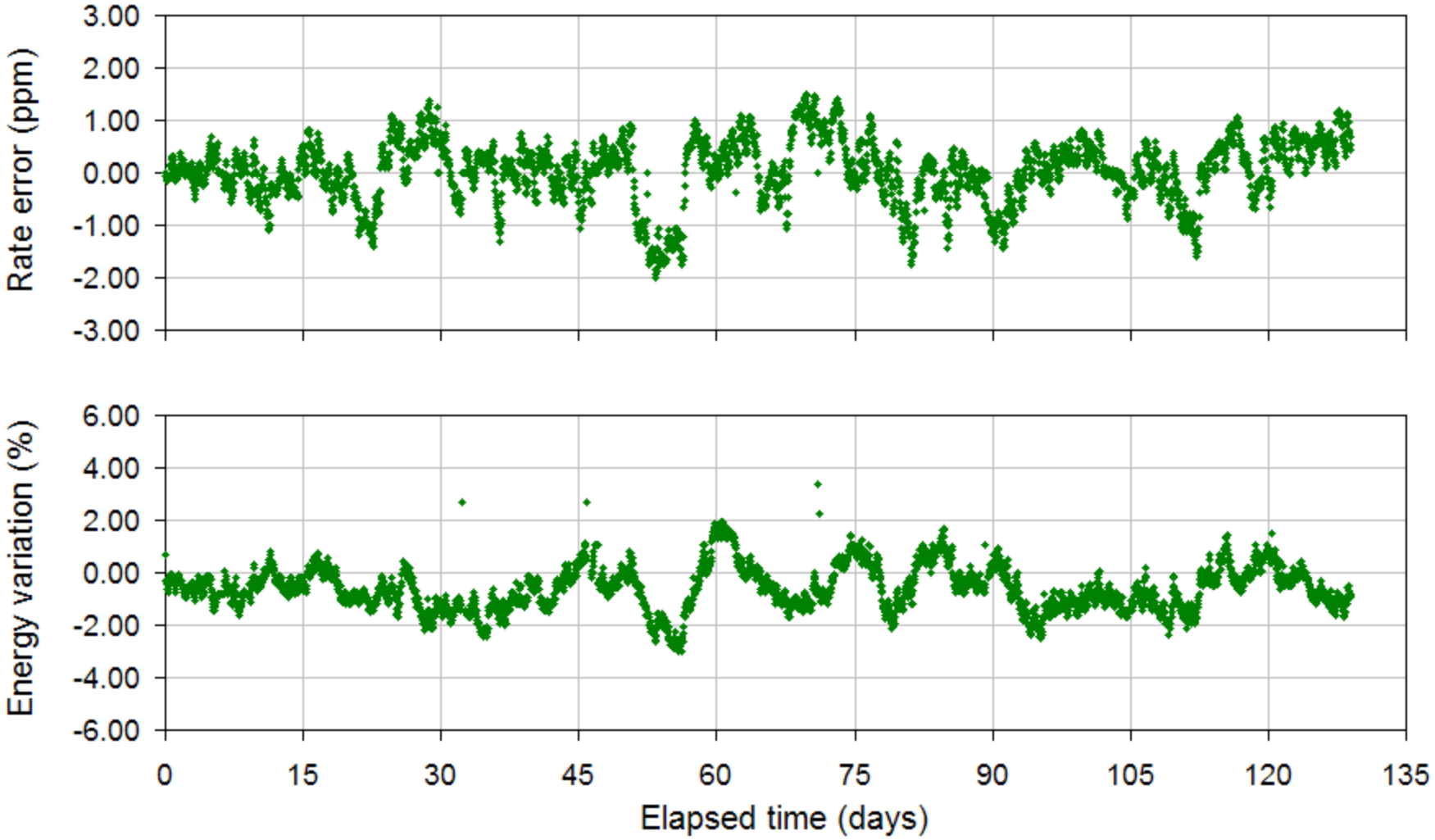
3) rate vs. barometric pressure



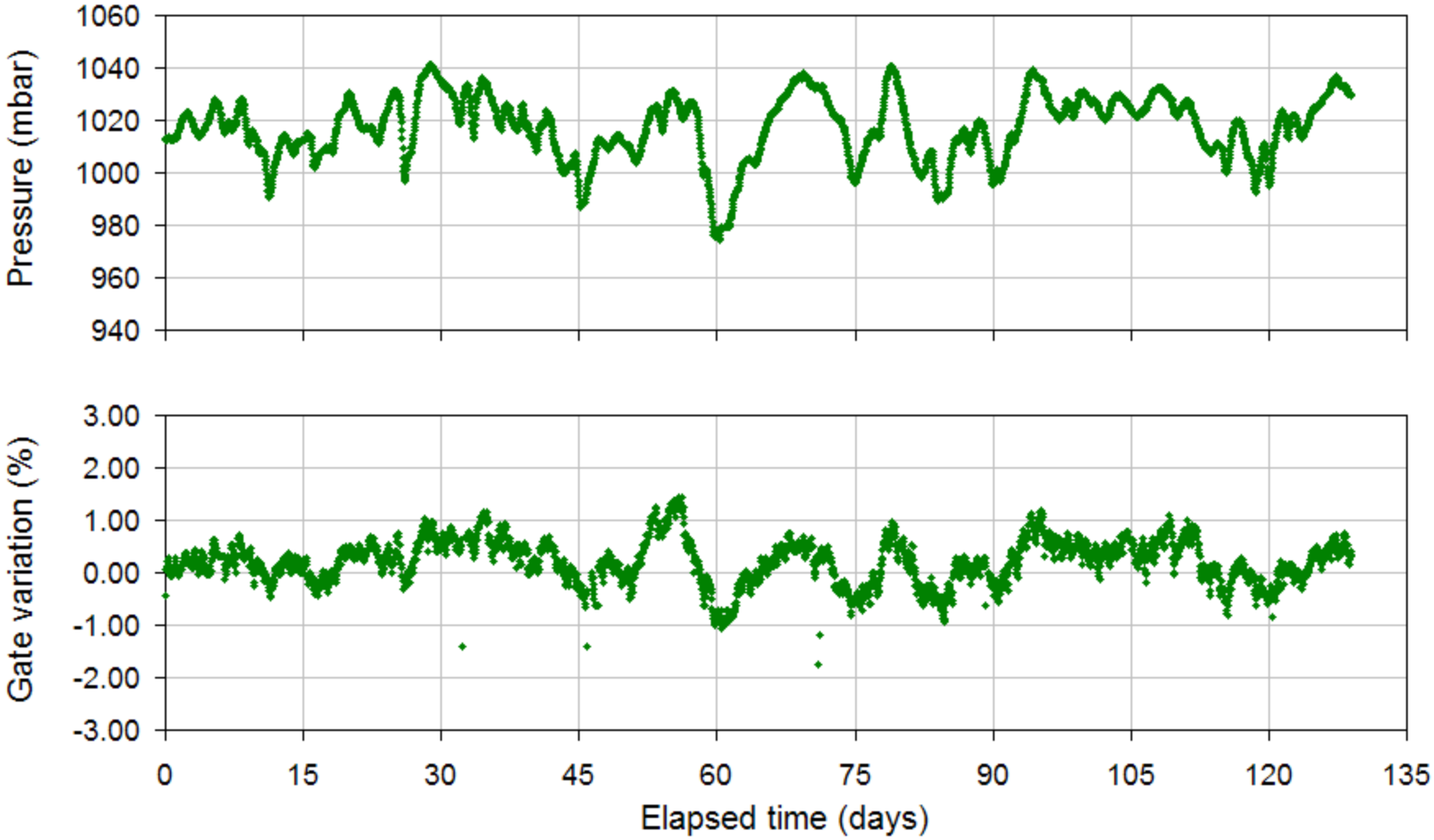
4) rate vs. “photogate time”



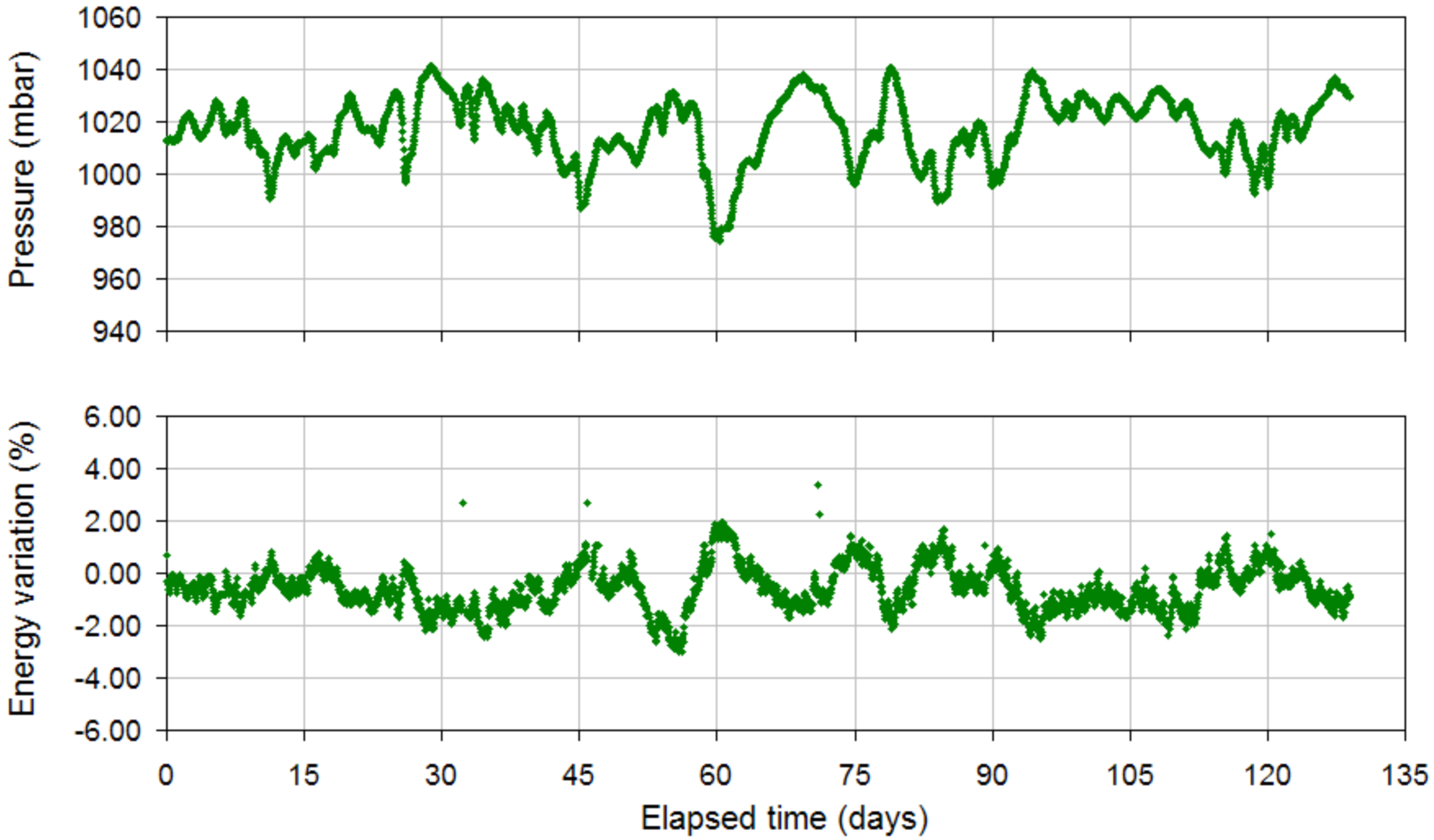
5) rate vs. energy



6) pressure vs. “photogate time”



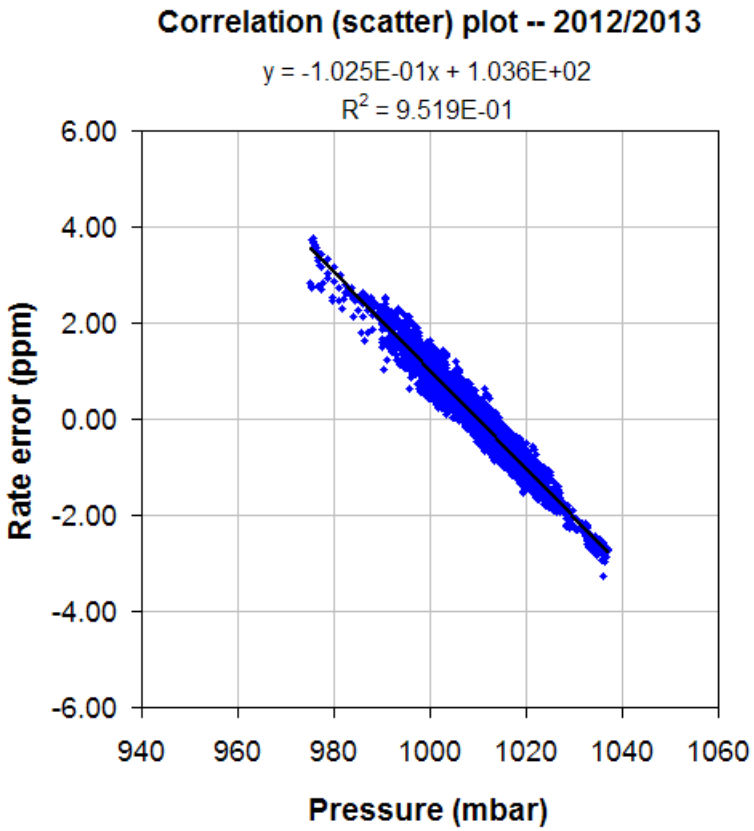
7) pressure vs. energy

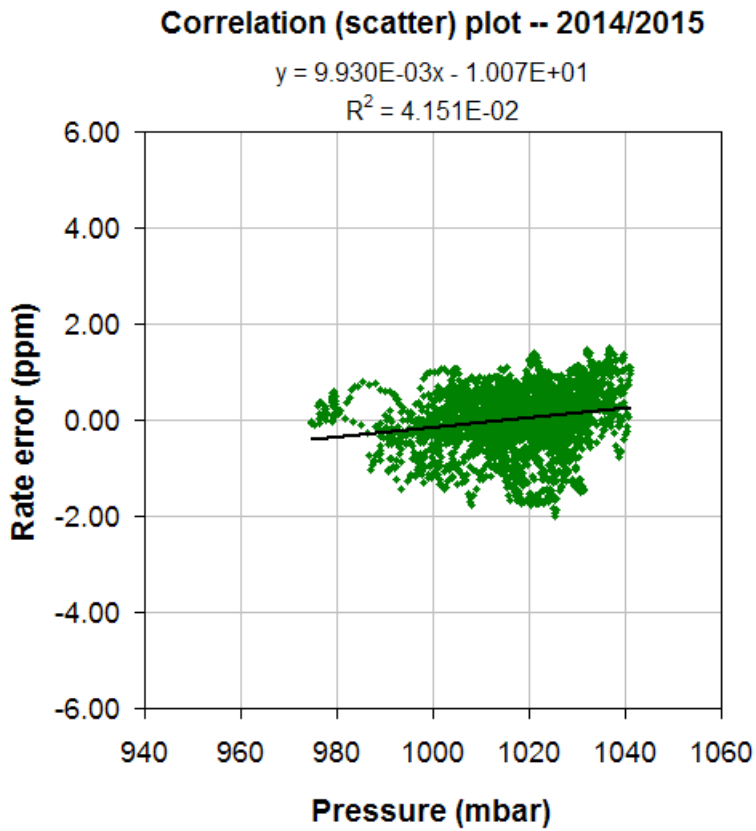


About environmental effects

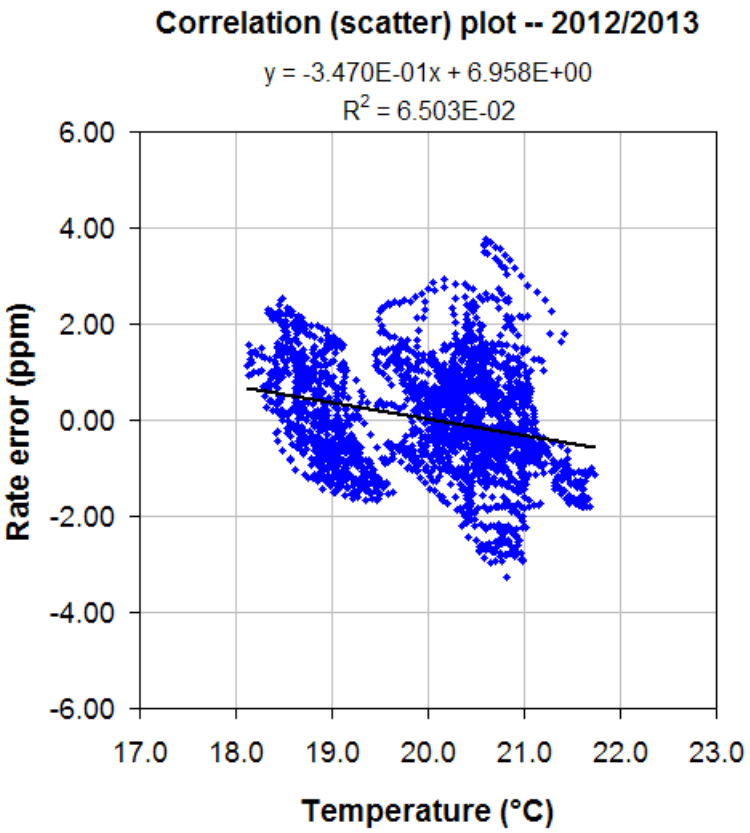
- Pendulum clock period T = $f(\theta) \cdot 2\pi\sqrt{L/g}$
  - goal: minimum variation in *L* or θ or E
- Long-term performance depends on:
  - temperature (absolute, relative, gradient)
  - atmospheric pressure, air currents
  - humidity
  - shock & vibration (air, ground, wall)
  - material stability or other disturbances
  - energy loss stability & energy gain stability

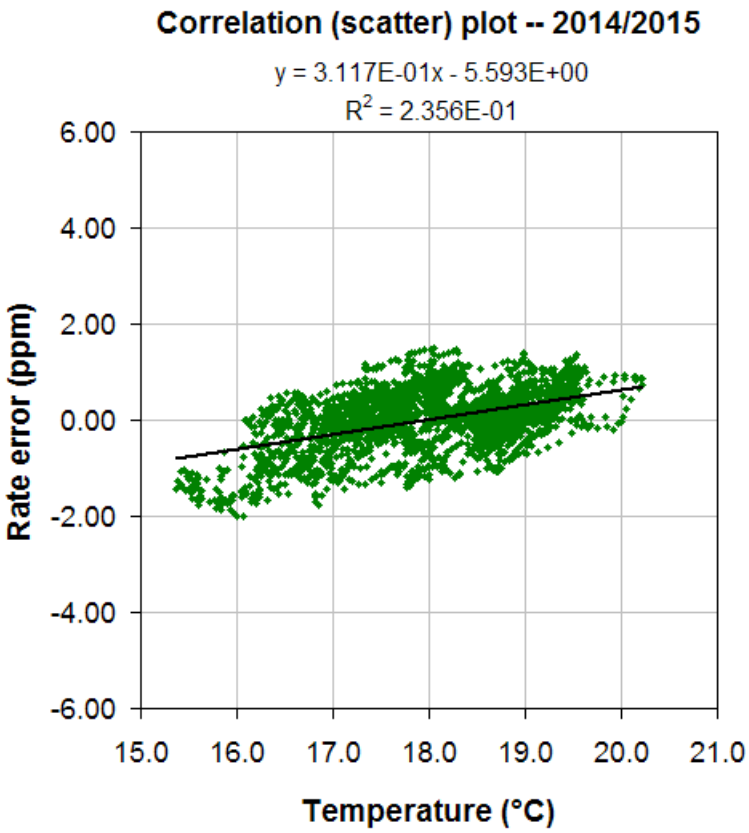
Correlation: rate/pressure



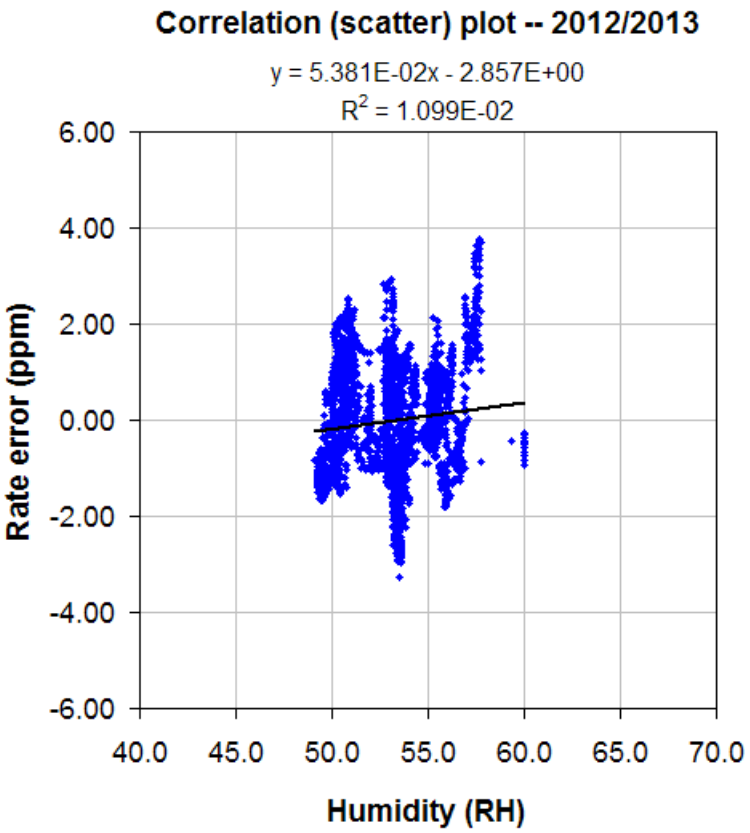


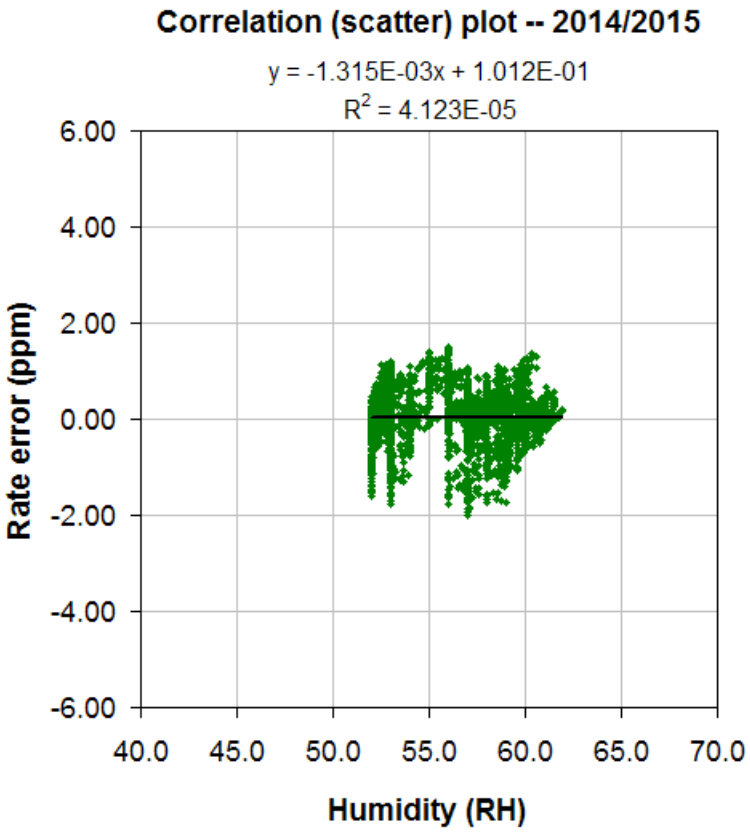
Correlation: rate/temperature



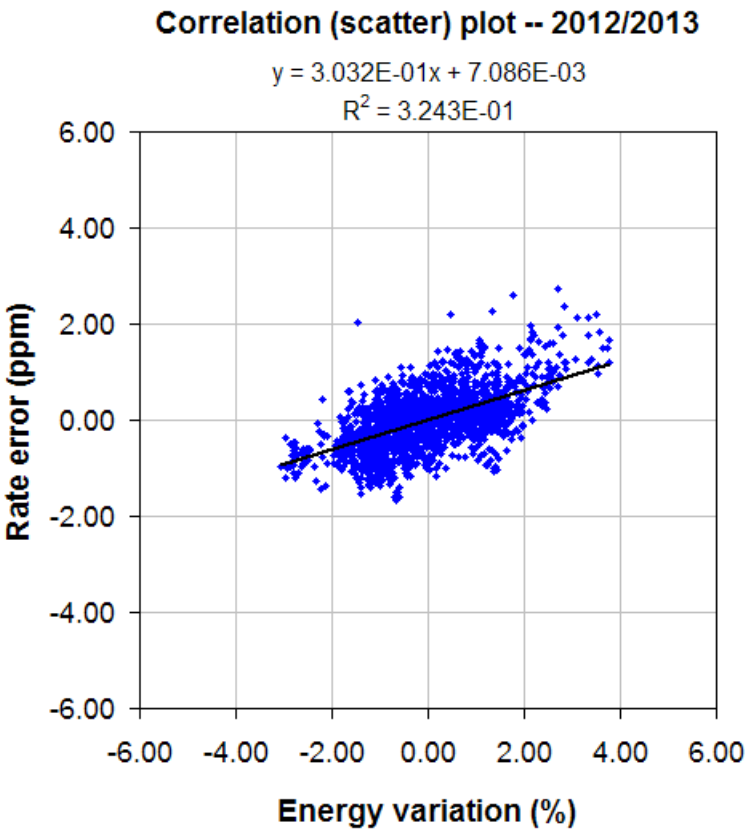


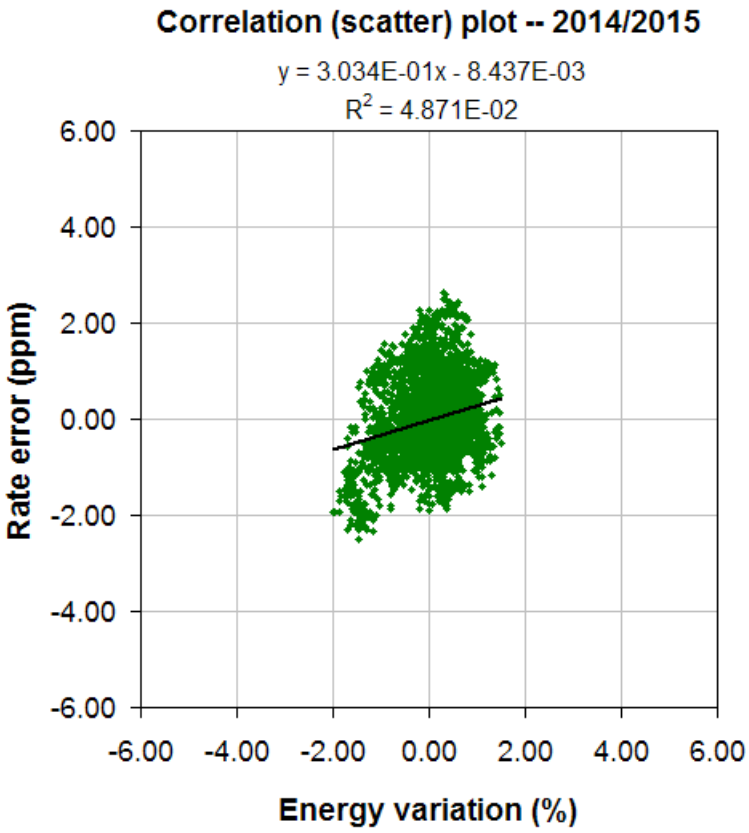
Correlation: rate/humidity



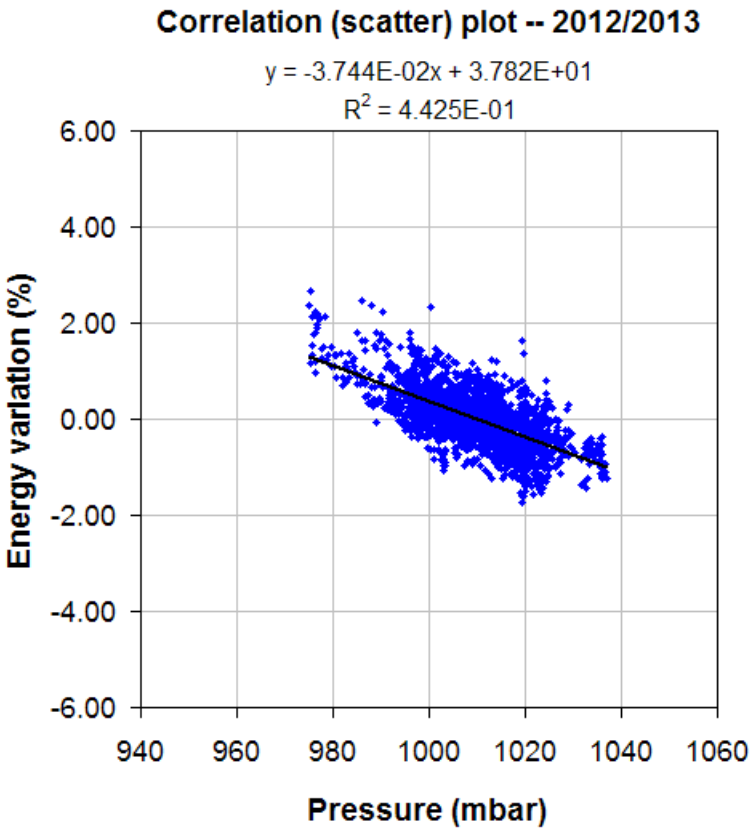


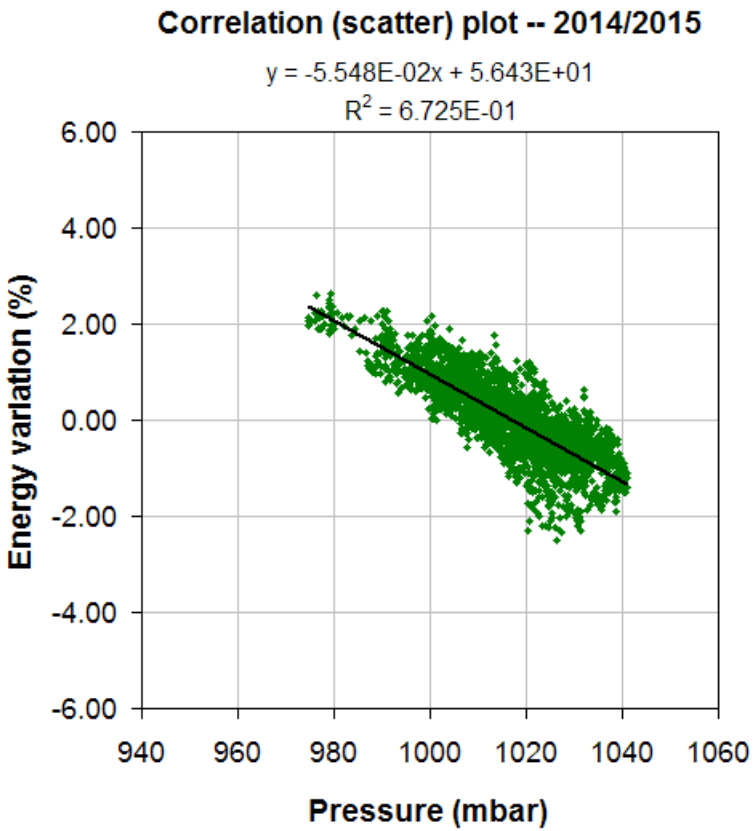
Correlation: rate/energy





Correlation: energy/pressure

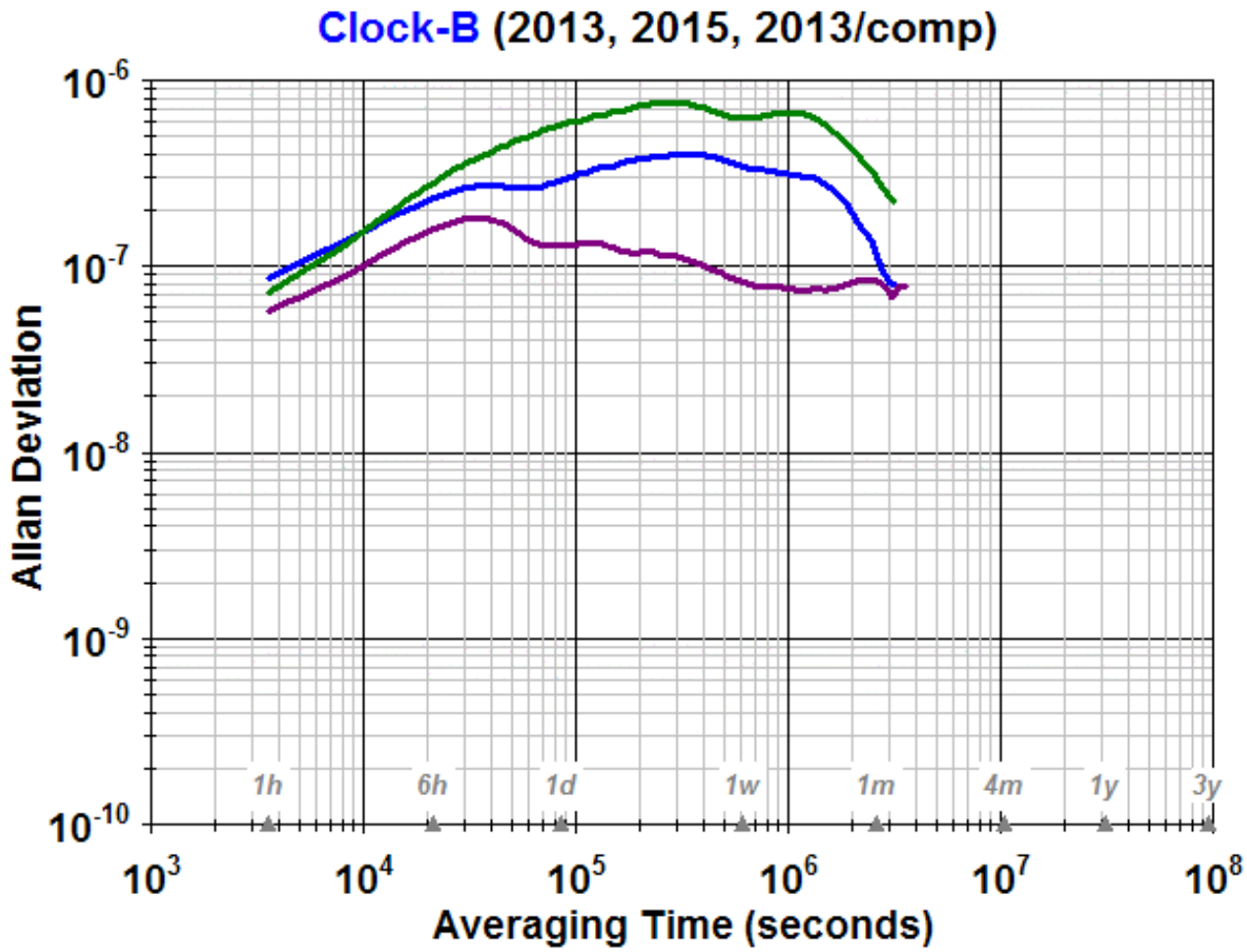




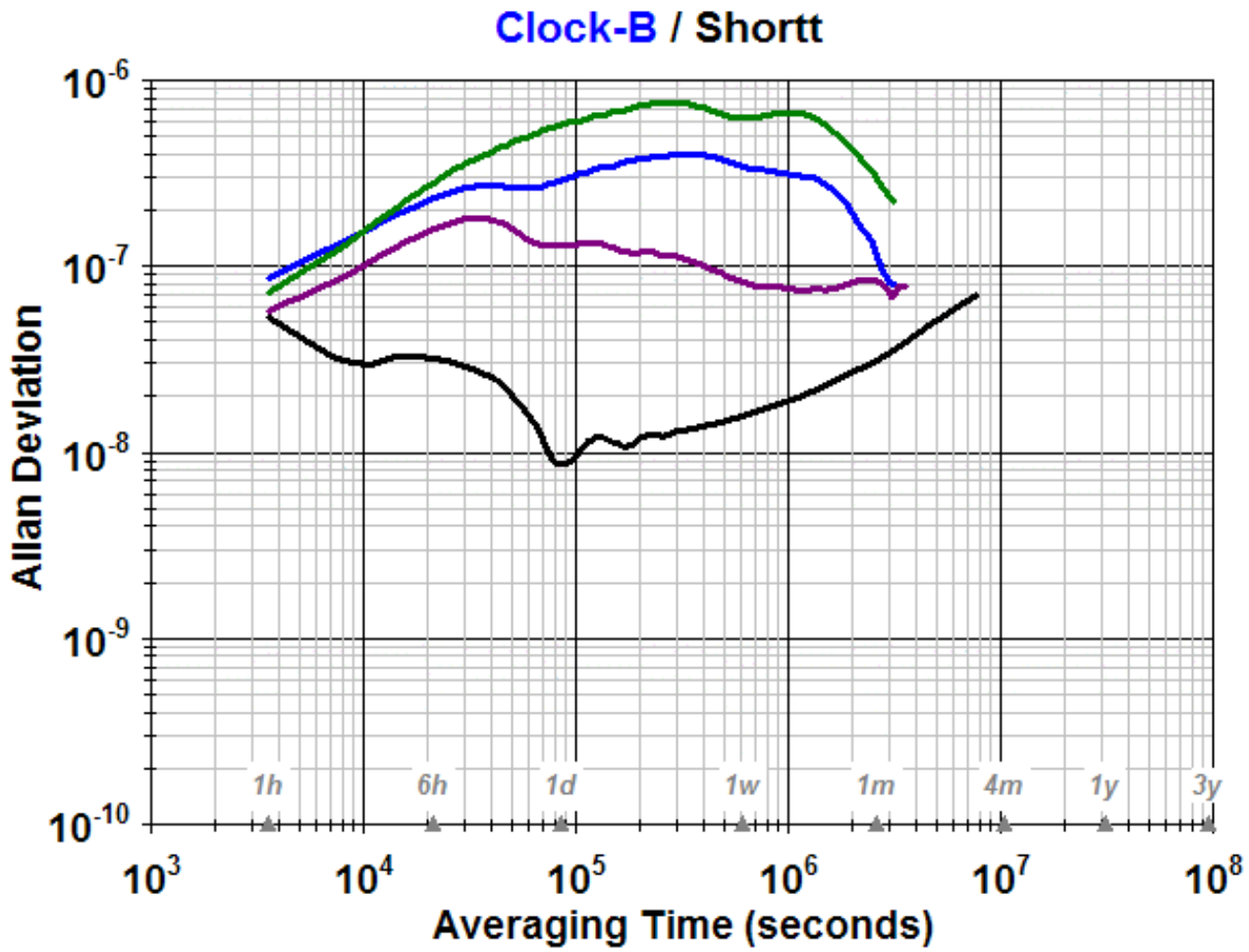
2015 summary

- Barometric pressure problem solved
  - correlation drops from 95% to 4%
- Humidity still has zero effect
- Temperature effect still very small
  - sign change −0.3 ppm/C to +0.3 ppm/C
  - same magnitude as before
  - but correlation increases from 6% to 24%

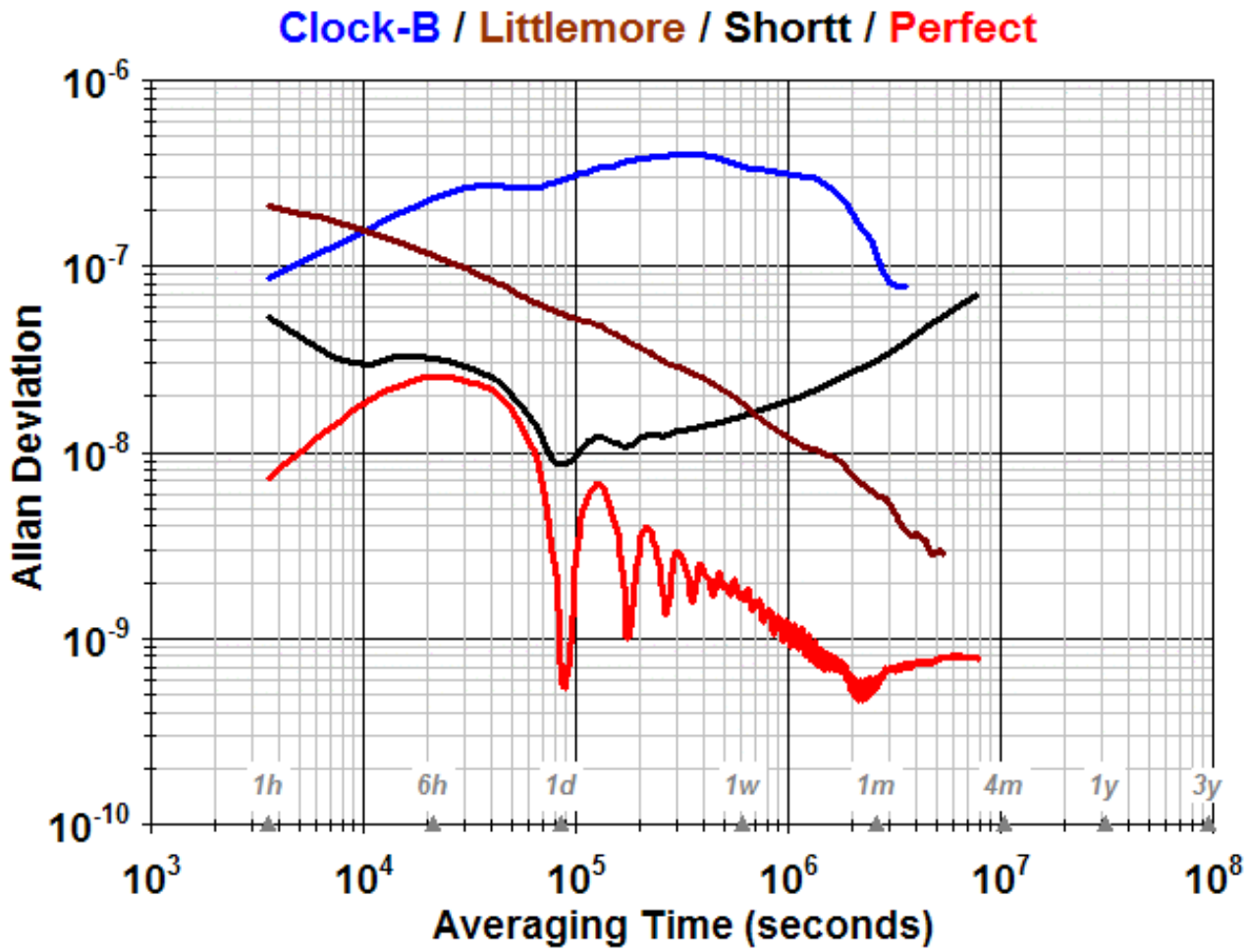
Clock B, Allan deviation



Clock B vs. Shortt #41



Clock B vs. best pendulum



5: Pendulum accuracy, P & Q

- There is confusion about pendulum Q
  - books, articles, letters endlessly debate
  - exceptions to simple EE model of Q
- Simple idea:
  - keep old **Q**uality-factor as originally defined
  - define new **P**urity-factor to highlight stability
  - focus on energy and energy stability
- Maybe this solves the “Q problem”

Pendulum accuracy (P and Q)

- Three energy values:
  - E is total energy (*large*)
  - ΔE is energy loss/gain per period (*small*)
  - σE is *variation* in energy each period (*tiny*)
- Accuracy (stability) is close to 1/PQ
  - P is "purity" factor (P = ΔE / σE)
  - Q is "quality" factor (Q = E / ΔE)
  - Note also 1/PQ = 1/(ΔE/σE·E/ΔE) = σE/E

Analogy: bag is E, spoon is ΔE

Analogy: spoon variation is σE

Analogy: measure ΔE and σE

Purity & Quality summary

- $Q = E / \Delta E$
  - energy efficiency (*quality*)
- $P = \Delta E / \sigma E$
  - energy consistency (*purity*)
- Stability = $1/PQ = \sigma E/E$
- Q is 100 to 100,000 or even 1,000,000
- P is 10 to 1,000 or even 10,000

Talk summary

- Perhaps P & Q model explains Clock B
  - allow designs with low Q but high P
- Clock B achieved stunning results
  - clock easily meets 1 second in 100 days
  - if it keeps going it may match Shortt #41
  - for long-term accuracy, at least
- Nice improvement 2013 to 2015
  - room for new temperature compensation

Thanks for your time

- Thanks to:
  - Jonathan Betts, Rory McEvoy (Greenwich)
  - Philip Woodward, Douglas Bateman (UK)
  - Bob Holmstrom, Bryan Mumford (USA)
  - HSN (Horological Science Newsletter)
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