Essl 290 2021

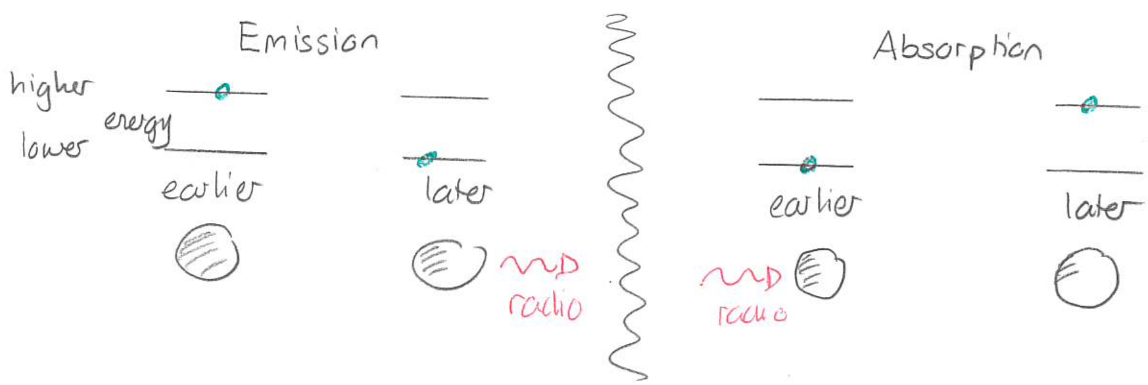
Lecture 42

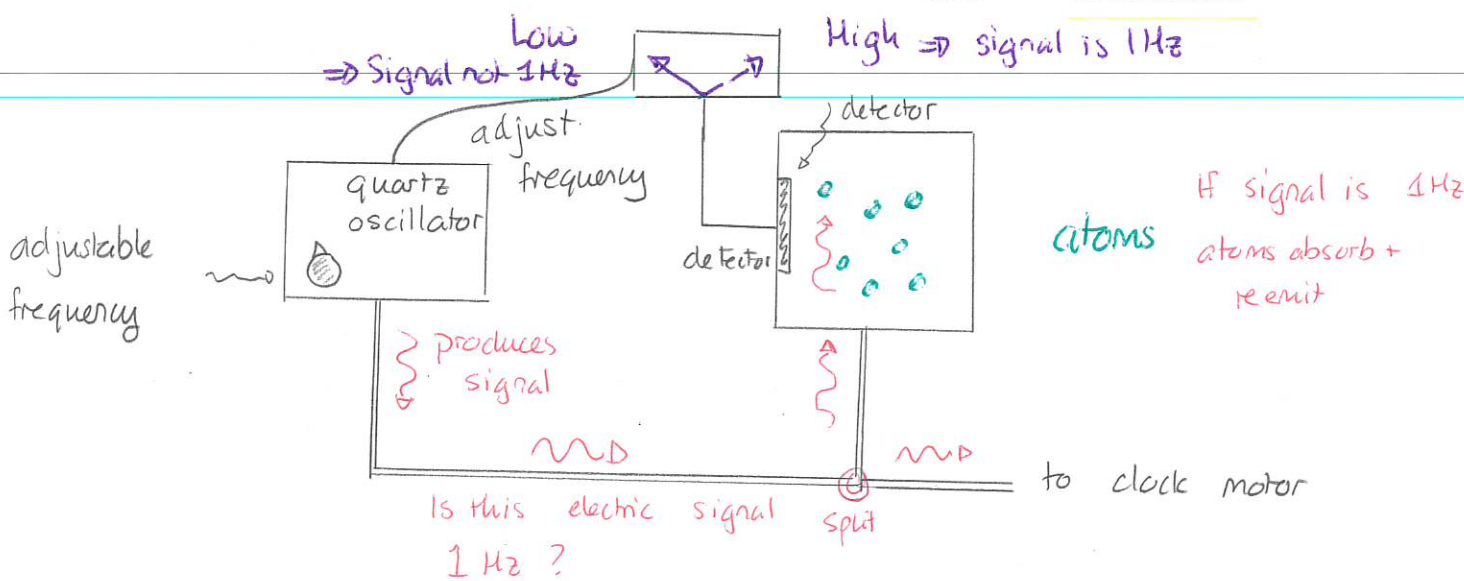
Weds: GPS, ...

Fri:

Atomic clock setup

An atomic clock uses the fact that atoms of a particular type absorb and emit light and other types of electromagnetic radiation at very specific frequencies. We can imagine a "toy model" of such an atom that can be used to design a clock that produces a 1 Hz signal.





Demo: Engineering Guy Video

Brief History of Atomic Clocks

Recall that quartz clocks had become the frequency and time standards from about 1930. The basic quartz clock had the following constraints.

1) it operated about 100 kHz   Lombardi   J Meas Sci 2007

2) it had an accuracy of 1 part in 10^7
   (lose about 0.01 s per day)

Some improvements by the 1950s resulted in a reduction in inaccuracy to about 0.0001 s per day (1 part in 10^9). However, there were some fundamental limitations to quartz crystal technology:

1) the operation of the crystal depended on its shape + size and therefore how it was fabricated. No two quartz crystals would be perfectly identical.

2) the frequency will change over time as the crystals age.
3) the frequency depends slightly on environmental conditions.
4) the maximum frequency appeared to be about 50 MHz.

The additional impetus for developing an even better frequency and time standard came from:

Forman, Proc. 7th PTTI Meeting 1985

1) microwave communications – the signals are transmitted by microwaves above 100 MHz (e.g. current cellphones ~1000 MHz)
2) radar communications – in the microwave range.
3) the desire for defining the second based on something other than Earth's rotation.

4) rapid development in the associated atomic physics.

The timeline is

1948-49 First clock regulated by an atomic system
* built by Harold Lyons at National Bureau for Standards (US)
* used ammonia molecules. (23.8 GHz)
* uncertainties of 1×10^{-7}, 2×10^{-8}
* not as accurate as best quartz regulators.

Forman pg 14 / Lombardi 2007

1955 First Cesium beam atomic clock
* built by Louis Essen at National Physical Lab (UK)
* used Cesium atoms (9.2 GHz)
* uncertainty of 10^{-9}

Lombardi 2007

1958-59 First Cesium beam atomic clock in US
* built by Natl. Bureau for Standards, Boulder
* used similar Cesium atom technology
* NBS-1 - accuracy 1×10^{-11}
* Replaced shortly after by NBS-2 0.8×10^{-11}

Demo - Show succession of these in Lombardi 2007 → Rather NIST pages

In the following decades these clocks have been refined repeatedly, eliminating and reducing various technical issues. More recent versions are:

Lombardi 2007

Name	Year	Accuracy	Loss in Seconds	Loses 1s in
NBS-3	1963-1970	5×10^{-13}	0.000016/year	63400 yr
NBS-6	1975-1993	8×10^{-14}	0.0000025/yr	400000 yr
NIST-7	1993-1998	5×10^{-15}	0.000000032/yr	32 million yr
NIST-F1	1999-	3×10^{-16}	0.0000000095/yr	106 million yr
NIST-F2	2014	1×10^{-16}	0.0000000032/yr	300 million yr

Show NIST video

1 Extreme clock accuracy

The NIST-F1 atomic clock loses about one second for every 3×10^{15} seconds that pass. This exercise explores this level of accuracy.

a) How many years does it take this clock to lose one second?

This level of accuracy is hard to fathom. Consider a similar level of accuracy in money management.

b) Roughly how accurately do you know you bank balance and the value of your other assets? To the nearest \$0.01, \$1.00, \$10.00, ...?

c) To give an idea the total household net worth in the United States is estimated to be about \$140 trillion. This is $\$140 \times 10^{12} = \$1.4 \times 10^{14}$. If we knew this to an accuracy of the amount to which you know the accuracy of your own assets, would this match the level of accuracy of the NIST-F1 atomic clock? If we knew the accuracy of the total worth to within a single dollar, would this match the level of accuracy of the NIST-F1 atomic clock? How much more or less accurate is this?

Answer: a) $1 \text{ yr} = \frac{86\,400 \text{ s}}{\text{day}} \times 365 \text{ day} = 3.15 \times 10^7 \text{ s}$

So $\frac{3 \times 10^{15} \text{ s}}{3.15 \times 10^7 \text{ s/yr}} = 9.5 \times 10^7 \text{ yr} \approx 100 \text{ million yr.}$

b) if one owns a house maybe to \$1000 or \$10000

If one does not or does not have a retirement fund maybe \$100.

c) Lets say to \$100 out of $\$1.4 \times 10^{14}$. This is

$\$1.$ out of $\$1.4 \times 10^{12}$

This is much less accurate than the atomic clock.

Even if we knew the national wealth with an accuracy of \$1 this would be

$\$1$ out of $\$1.4 \times 10^{14}$

and this would be a tenth of the accuracy of an atomic clock.

We would need to know the national wealth with an accuracy of a dime.

2 Reference standard for time

Throughout this course we have encountered various epochs of timekeeping

Ancient times: Sundials, water clocks,

Medieval times: Sundials, water clocks, verge-and-foliot clocks

17^{th} – 18^{th} centuries: Pendulum and balance-spring clocks, precision chronometers

19^{th} century: Time standardization, electrical time-signaling

Early 20^{th} century: Quartz timing standards and clocks

Mid 20^{th} century – present: Atomic clocks

a) During each period what served as the ultimate authority or reference against which the accuracy of any device could be checked? What are the issues with this reference?

b) During each period were there any better alternative ultimate references?

Answer a) Definitely the Sun or other celestial bodies. One would
b) track their apparent motion - local noon etc,...

Issues : * Seasonal variation (eqn of time)
* Difficulty of observation
* Limited accuracy of observation
* Is Earth's rotation uniform?

The only exception is an atomic clock. This relies on basic features of specific atoms. There appears to be less variability here than with Earth's motion.

Redefinition of the second

Until the mid 20th century the basic definition of the second refered to the apparent motion of the Sun, Moon + stars. This was

$^1/_{86400}$ of the mean solar day – noon to noon
- includes corrections such as equation of time

By the mid 20th century it appeared that Earth rotated at a variable rate. This lead to the redefinition of the second as the fraction of the tropical year of 1900.

Once the Cesium clock became operational it was clear that it could serve as a more reliable time standard. The particular frequency there had been measured to be (by 1957)

$$9\,192\,631\,770 \underbrace{\pm 20\,\text{Hz}}_{\text{error}}$$

Then the second was defined as

9192631 770

cycles of this particular energy transition of the Cesium atom. (1967/8)