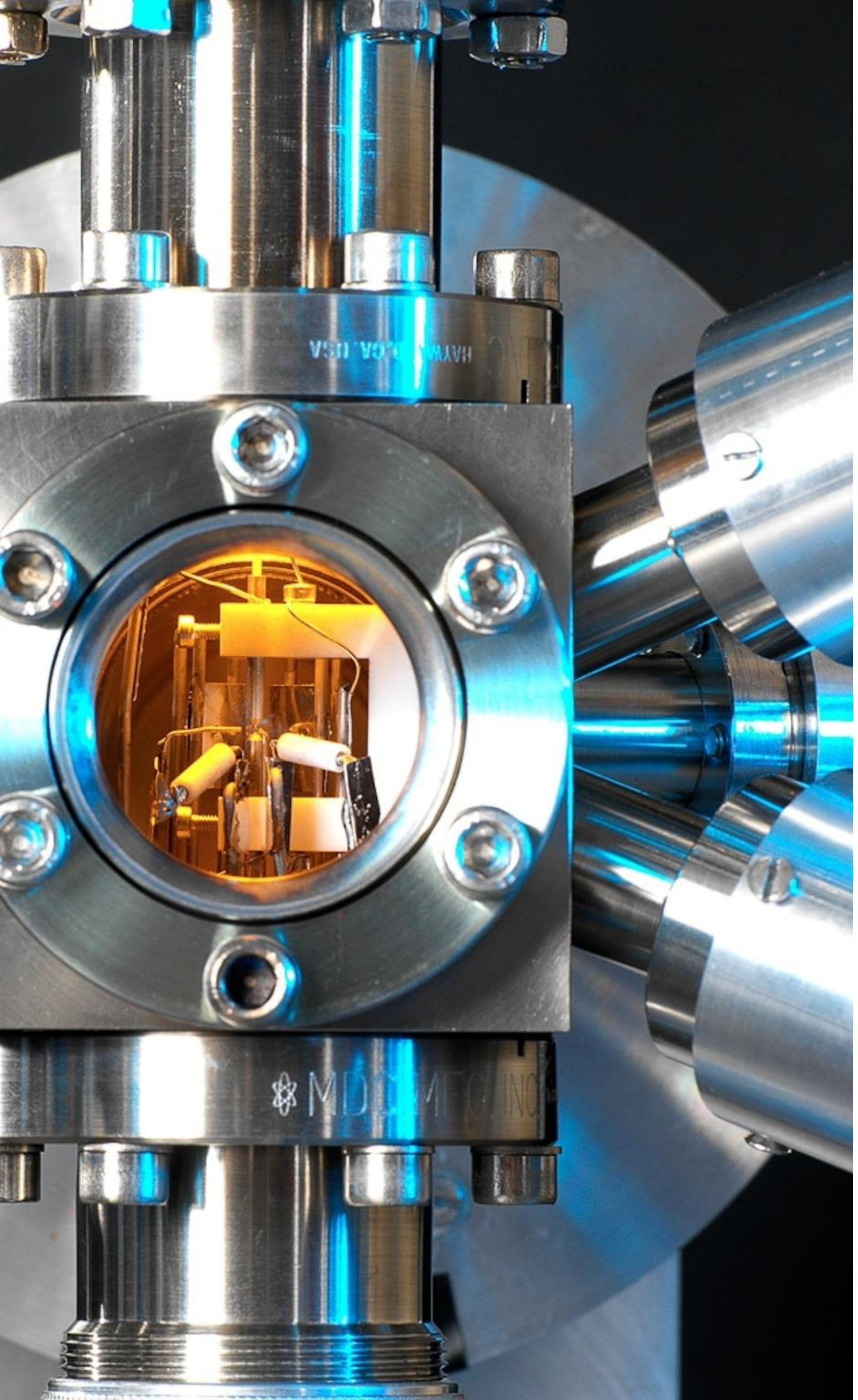


Modelling Hybrid Techniques for Time Sourcing and Distribution

Dylan Miah

Atomic Clocks

Atomic clocks are clocks that use a frequency reference f which corresponds to the frequency required for transition between hyperfine ground energy levels.

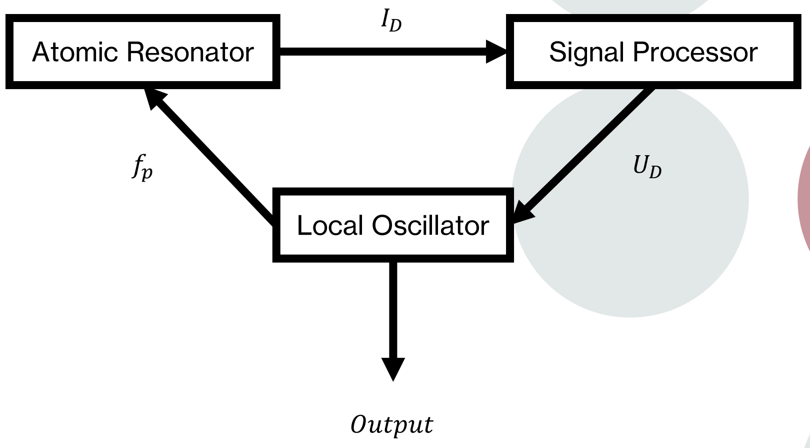
$$f = \frac{\Delta E}{h}$$

Passive atomic clocks work on a feedback loop with 3 main components:

Local Oscillator – a quartz oscillator that generates a probing EM wave with the frequency f_p which is passed through to the atomic resonator. The oscillator output is also passed through a counter that counts the number of oscillations and keeps time.

Atomic Resonator – prepared ground-state atoms/ions are bombarded with the EM waves and undergo excitation. The excited atoms are counted by a detector, and the rate of excitation is recorded and the response signal I_D is generated.

Signal Processor – any deviations in the expected rate of excited atoms I_D results in the signal generator producing a control voltage to the oscillator to alter the frequency so that $f_p = f$.



Andreas Bauch et al (2003)

Why caesium?

The definition of the SI second is

“[...] taking the fixed numerical value of the caesium frequency, $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9192631770 when expressed in the unit Hz, which is equal to s^{-1}. ”

Caesium has features that allow it to be a suitable time keeping frequency standard.

(i) Interaction time of absorption of the microwaves is long allowing for easier conversion to count.

(ii) Probing microwaves are easy to generate.

(iii) Low atomic velocity.

(iv) Energy is insensitive to EM fields.

The last two provide a minimisation in frequency drift making the caesium clock an ideal precise measuring tool.

Andreas Bauch et al (2003)

Universal Time

Universal Time is the time of the Earth axial rotation with respect to the sun (24-hour solar day) observed locally at the Royal Observatory in Greenwich, UK counted from zero hours at mean midnight.

There are three types of UT to account for corrections.

UT0: The standard UT with no corrections.

UT1: UT0 with corrections needed to account for polar effects due to Chandler wobble.

UT2: UT1 with corrections for seasonal fluctuations.

Usually, UT1 is the standard required to construct UTC.

BIPM (2009)

UTC(k) & NPL

Globally, 80 institutions contribute to the construction of Co-ordinated Universal Time (UTC) with 450 atomic clocks and 12 primary frequency standards. Each institution measures UTC(k) time with their atomic clocks.

For the UK, the *National Physics Laboratory* is the domestic distributor of UTC(NPL) time. The atomic clock used for this distribution is a hydrogen maser clock.

Caesium fountains are used as primary frequency references at NPL. These references help steer UTC(NPL) to the correct time – which is done daily.

BIPM (2009)

Progress towards Optical Clocks

Standard caesium-133 clocks operate on the fact the energy transition between states $F_g = 3, F_g = 4$ can be induced by microwaves. To progress in resolution and accuracy in atomic clocks technology, higher frequency waves are desired.

Optical atomic clocks use light (LASER) frequency as the standard for the clock. The general mechanism for time keeping is the same for caesium atomic clock with the main key differences being the inclusion of optical combs.

Optical clocks have two main benefits:

(i) High frequency light waves allows for more degrees of precision.

(ii) Optical clocks are more stable with a lower Allan variance.

The debate to change the definition of the SI second with respect to optical methods is ongoing in ITU.

Andre D. Ludlow et al (2015)

VCXO & CSAC

Voltage controlled crystal oscillators (VCXO) are oscillating quartz crystal that are foundational to many clocks. These are desirable oscillators as they provide easy conversion between electrical and mechanical oscillations via the piezoelectric effect.

Base station distributors in the UK of time often used VXCO clocks with UTC(NPL) references to distribute time for civilian use.

Chip size atomic clock (CSAC) are very small commercial atomic clocks initially commissioned by the US Defence and were first developed by Microsemi. CSAC were created to avoid reliance on GPS in cases of jamming.

CSAC used coherent population trapping pioneered by NIST as the core ionic trapping mechanism.

Although commercially available, CSAC are expensive to manufacture so have not been used for everyday clocks.

Peter Cash et al (2018)

Stability & Uncertainty

Over time, a clock undergoes a frequency drift which results in uncertainty of the time.

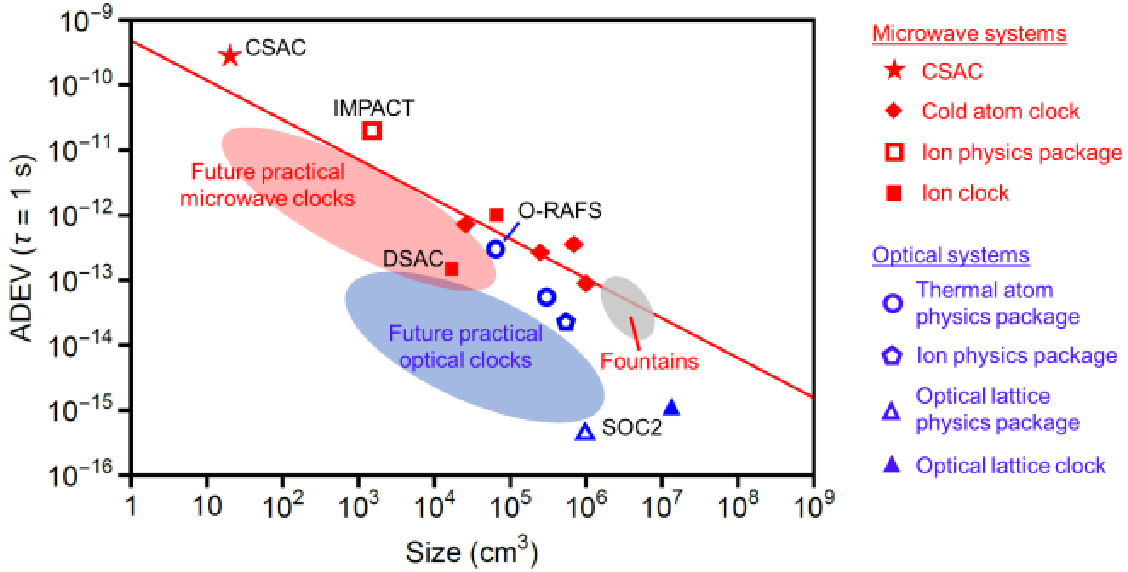
For atomic clocks, possible uncertainties could arise from:

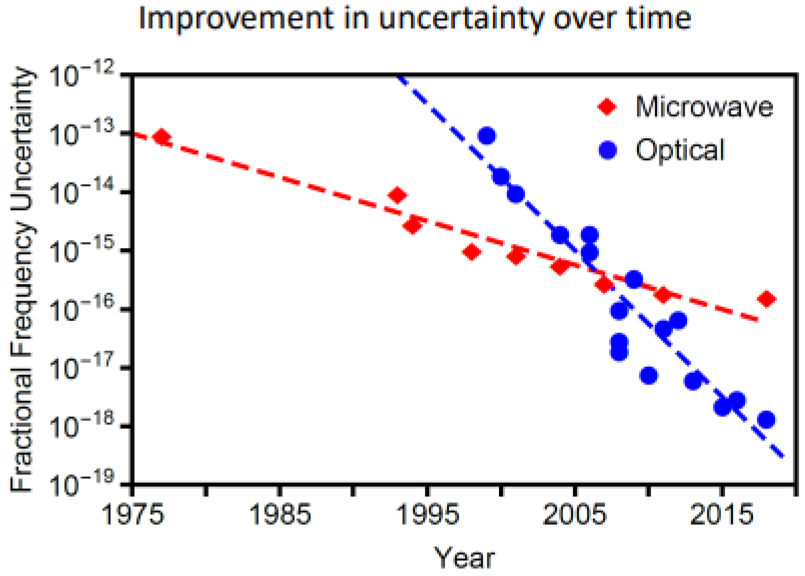
- Electronics.
- The doppler effect.
- The geometry (phase between each exit point) of the Ramsey Cavity.
- Environmental differences (temperature and humidity).
- Zeeman frequency shifts.

All clocks have a noise factor which determines instability of the clock. Particularly, atomic clocks have white (phase noise) and pink noise (flicker frequency noise). The instability is measured by the Allan variance $\sigma_y^2(\tau)$ over a time τ which is a mathematical metric that encodes the power of each type of noise.

Andreas Bauch et al (2003)

The Journal of Measurement Science (2007)





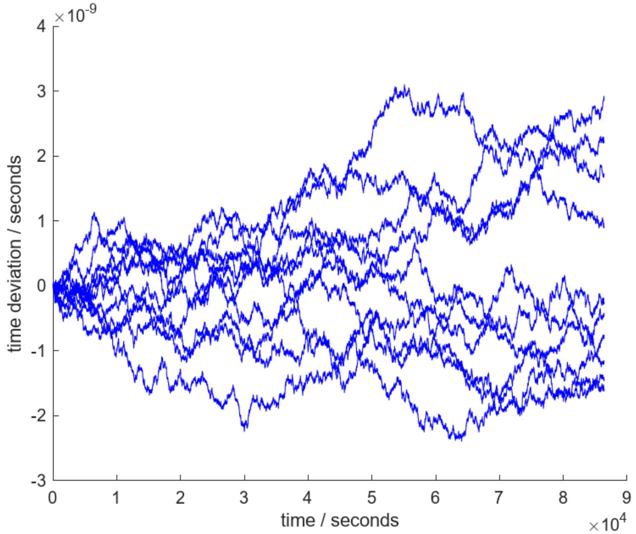
	Caesium	Rubidium	Optical	CSAC	VCXO
Frequency Drift (daily)	$<1 \times 10^{-15}$	$<8.64 \times 10^{-15}$	$<4.83 \times 10^{-18}$	$<3 \times 10^{-11}$	$<1.59 \times 10^{-13}$
Allan Variance	1×10^{-13} at $\tau = 1\,s$ 1×10^{-15} at $\tau = 10^4\,s$	5×10^{-12} at $\tau = 1\,s$ 1.5×10^{-14} at $\tau = 10^5\,s$	1.3×10^{-15} at $\tau = 1\,s$ 2.9×10^{-17} at $\tau = 10^3\,s$	9×10^{-10} at $\tau = 1\,s$ 1×10^{-12} at $\tau = 10^3\,s$	5×10^{-11} at $\tau = 1\,s$ 1×10^{-10} at $\tau = 10^5\,s$
Uncertainty over a Day	10^{-10} s	10^{-9} s	10^{-13} s	10^{-5} s	10^{-3} s

Physical Review Letter (2015)

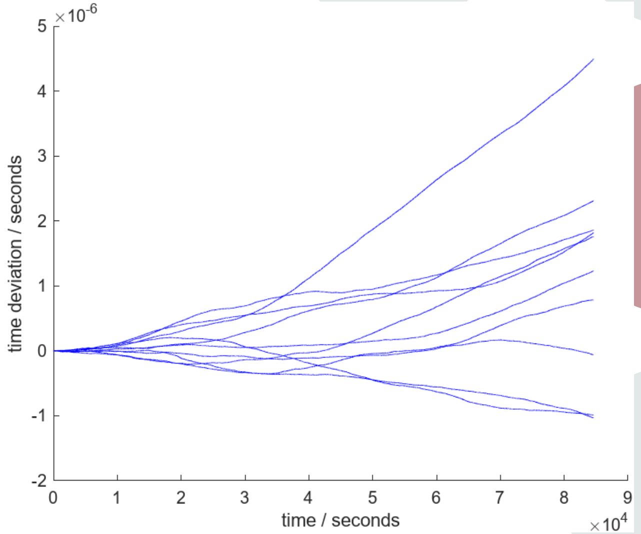
B. L. Schmittberger & D. R. Scherer (2020)

Clock Modelling

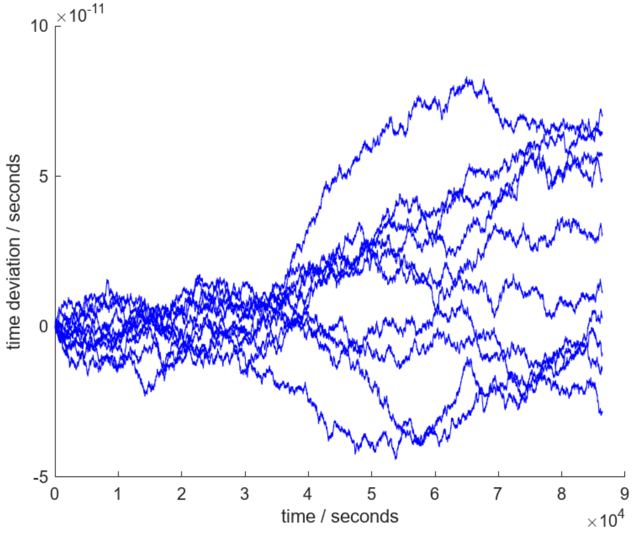
Rb Atomic Clock



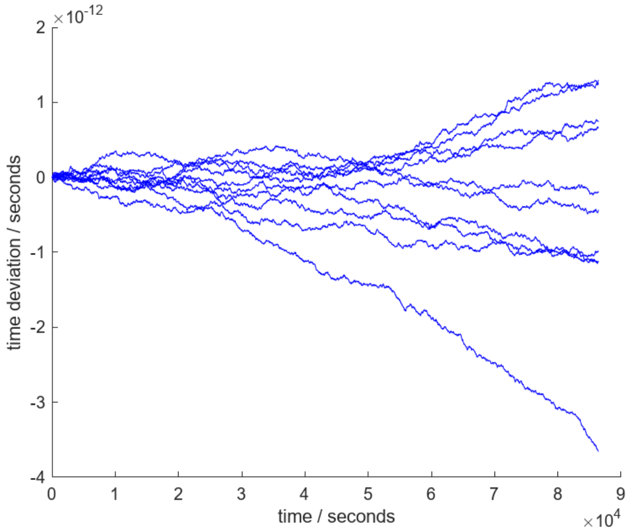
CSAC Clock



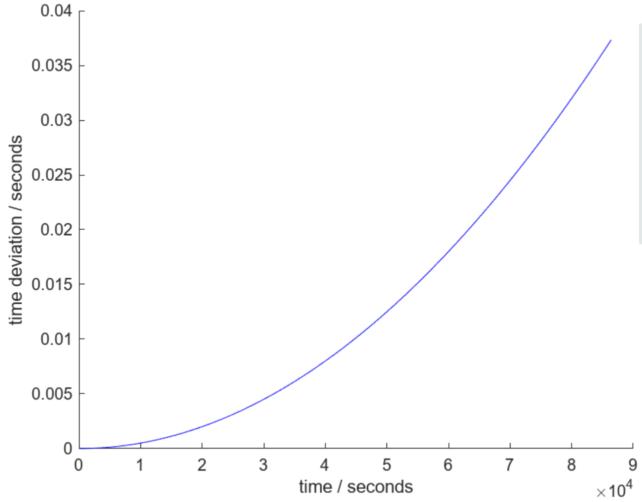
Cs Atomic Clock



Optical Clock



VCXO Clock



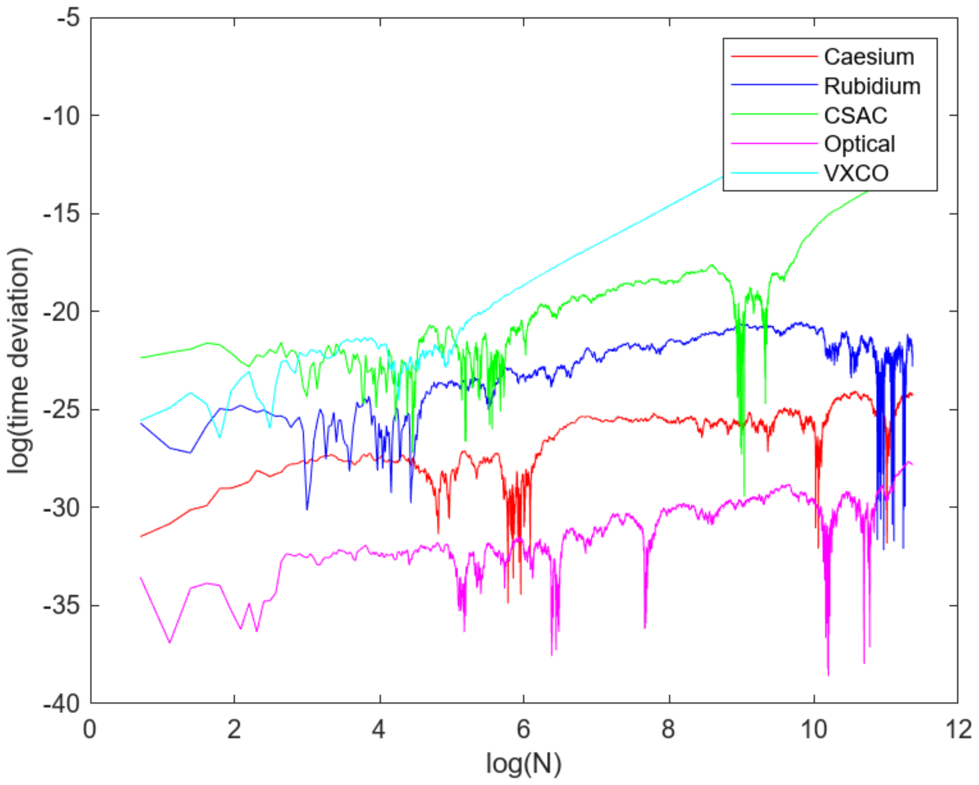
C. Zucca & P. Tavella (2005)

C. Zucca & P. Tavella (2015)

Clock Comparison

Our clock model seems to match standard results with optical clocks preforming the best and VCXO clocks preforming the worst.

Another simulation was ran with 100 clocks over a 6-hour interval to obtain absolute mean uncertainty and standard deviation of the time deviations from true time for each clock.



	Caesium	Rubidium	Optical	CSAS	VCXO
Absolute Mean	9.1×10^{-11}	6.8×10^{-10}	2.3×10^{-13}	2.3×10^{-7}	1.4×10^{-2}
Standard Deviation	6.8×10^{-11}	4.4×10^{-10}	1.7×10^{-13}	1.9×10^{-7}	$1.1 \times 10^{-17}\ s$

Distributing Time

Time dissemination is the process of distributing time from timing sources. For example, terrestrial time dissemination protocols distribute UTC(NPL) time to telecom core networks then to UK base stations for public and private access.

Often in such distribution networks there is a combination of different dissemination techniques and clock types used. However, since the release of the Blackett Review (2018), it has been identified that PNT systems in the UK rely heavily on GNSS.

A reliance on GNSS causes potential problems such as,

- Jamming
- Spoofing
- Multipath Dispersion
- Solar Weather

An interest in terrestrial based time distribution should be considered for UK infrastructure.

This project investigates two ethernet solutions for time distribution:

- White Rabbit developed by CERN.
- ELSTAB developed by the AGH University of Science and Technology.

Blackett Review (2018)

White Rabbit

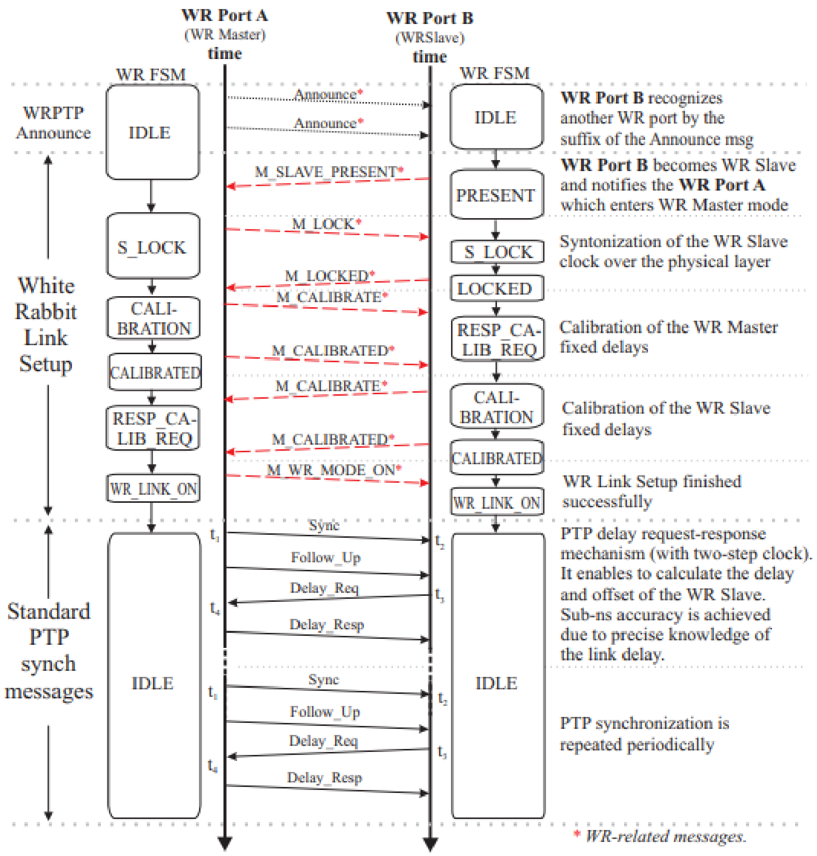
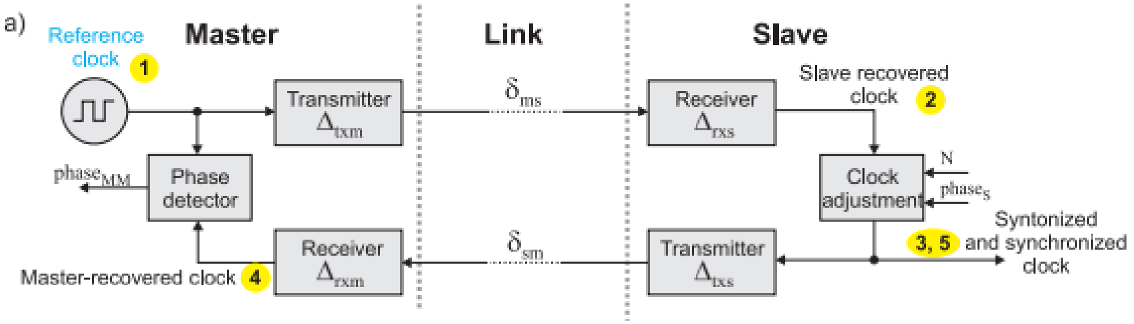


Fig. 2. Simplified overview of the message flow in WRPTP.

White Rabbit is a hybrid ethernet solution to time distribution. It was developed by CERN to have sub-nanosecond accuracy and picosecond precision.

There are three key components for white rabbit to achieve synchronisation:

1. **Initial calibration:** a message exchange between the master and slave clock to determine physical hardware delays.
2. **Synchronous Ethernet (SyncE):** a PLL system which adjusts the frequency of the slave clock to the frequency of the master clock (ITU protocol).
3. **Precision Timing Protocol (PTP):** a protocol ran continuously to calculate the time delay between the master and slave clock and adjust the slave clock accordingly (IEEE protocol).



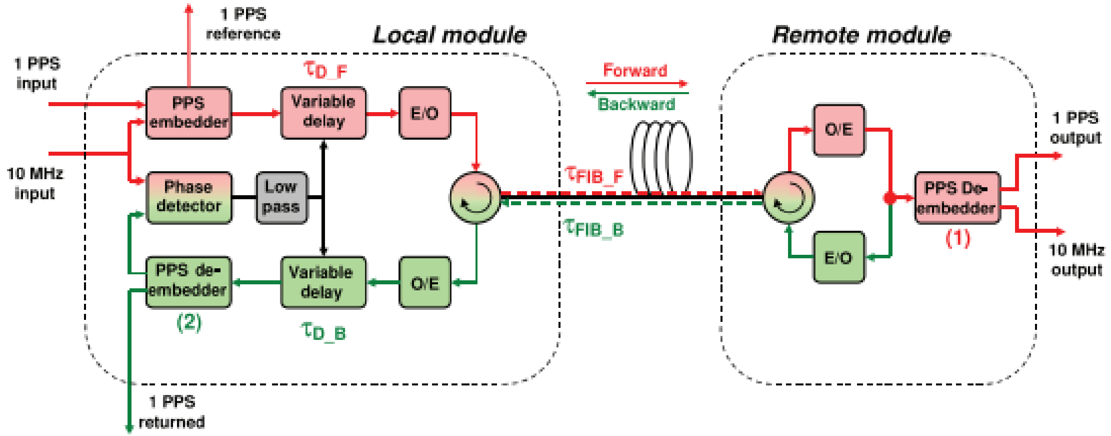
Tomasz Włostowski (2010)

Electronically Stabilised Fibre Optic (ELSTAB)

ELSTAB is another hybrid ethernet solution developed by AGH University of Science and Technology. Under idealised conditions, picosecond accuracy can be achieved with ELSTAB.

The key components to ELSTAB that differs from White Rabbit is

- **DLL system:** a delay-locked loop fixes the delay time between the master. Any difference in phase adjusts the master clocks phase using delay lines to ensure the delay remains constant. This results in a faster and more accurate lock than a PLL system.
- **Ideal Conditions:** the delay uncertainty along optic fibre under ideal conditions such as fixed temperature and refractive index minimises fluctuation and thus allows for picosecond precision.



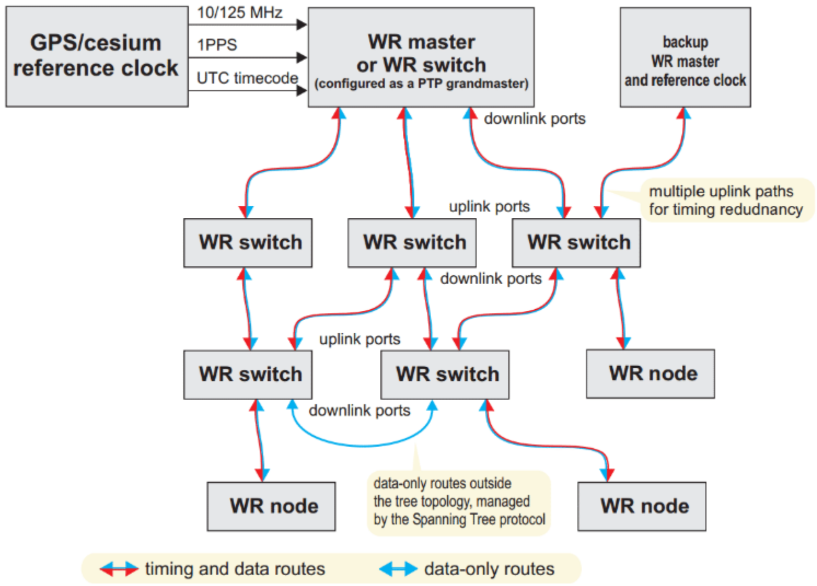
P. Krehlik et al (2016)

Boundary & Transparent Clocks

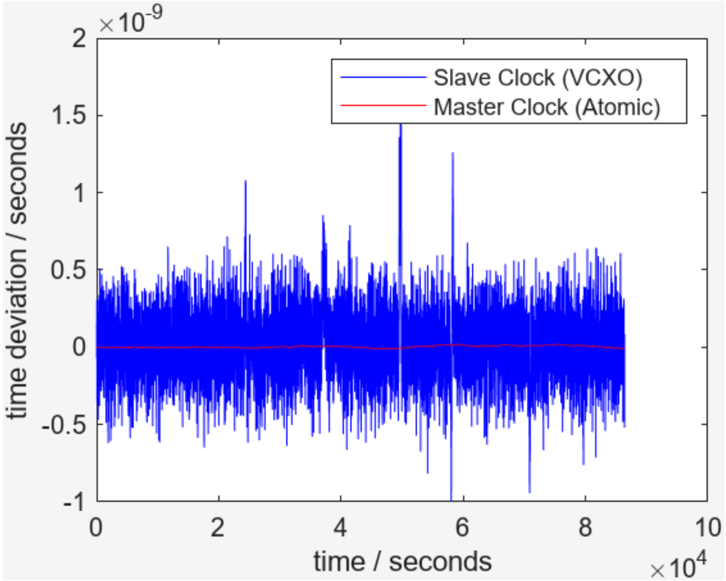
Between a grandmaster and a slave clock, a boundary clock/switch act as a slave to the grandmaster and a master to the slave clock. This allows for more efficient and accurate time distribution

Transparent clocks are clocks that only relay messages for the PTP protocol, marking their timestamp for when they receive and send data for the PTP protocol. This reduces noise occurring from long distances.

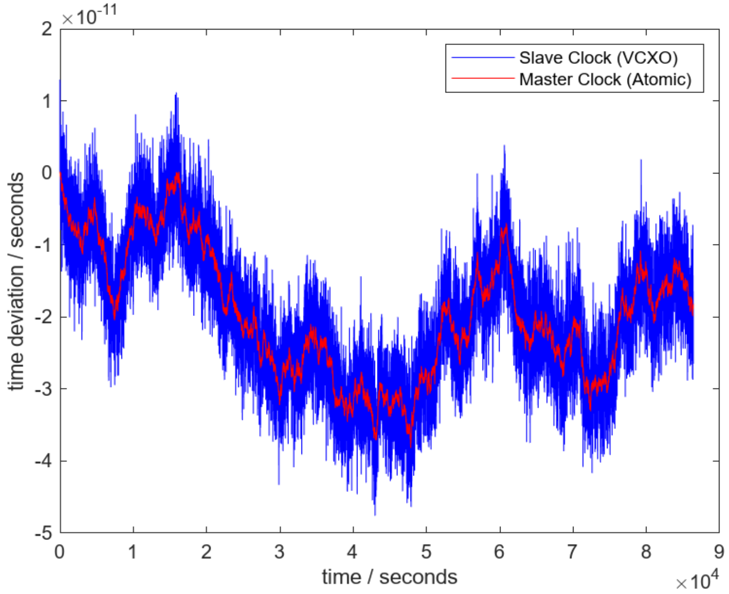
A distribution network is often hierarchical with a grandmaster clock (usually UTC(NPL)) connected to boundary, transparent and slave clocks.



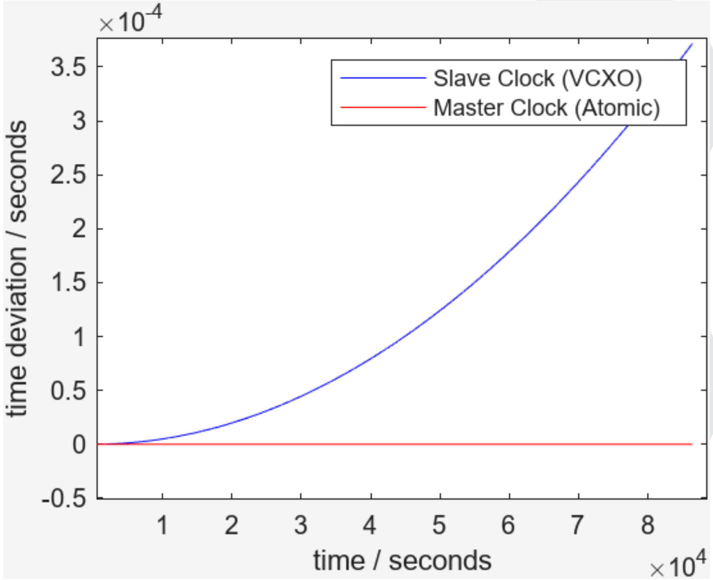
Time Dissemination Modelling Comparison



Locked mode with
White Rabbit



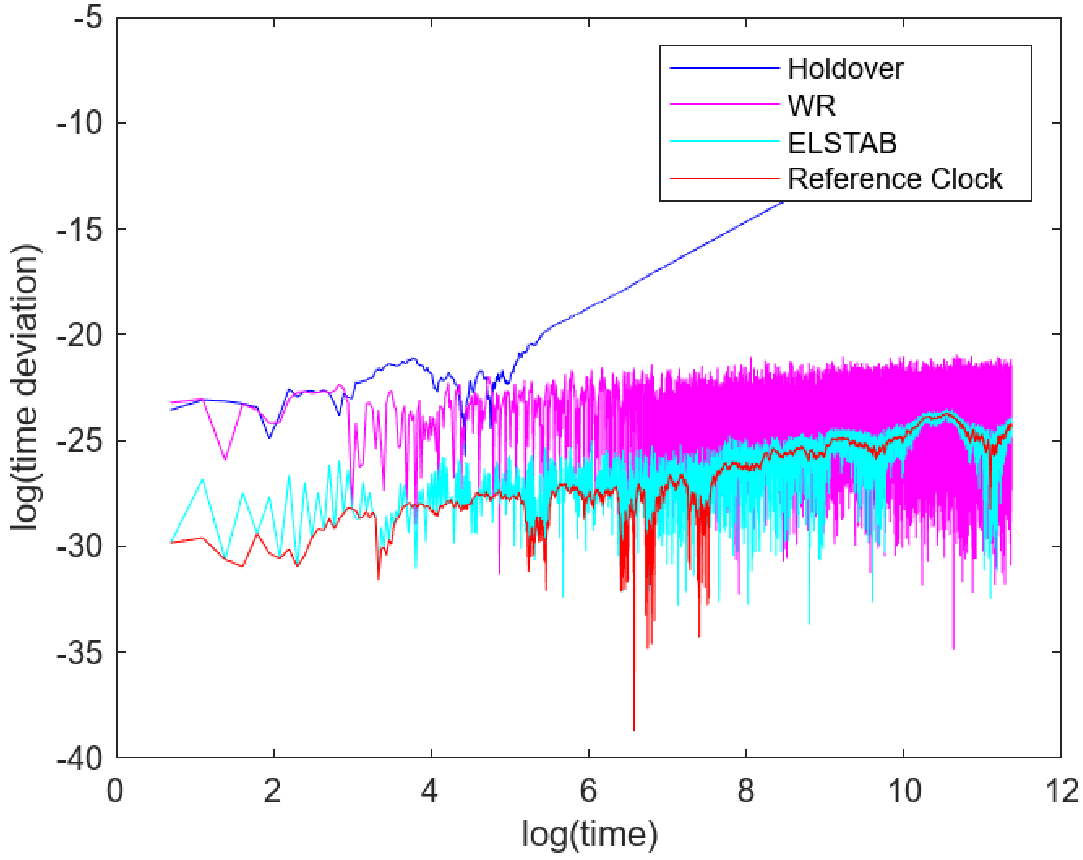
Locked mode with
ELSTAB

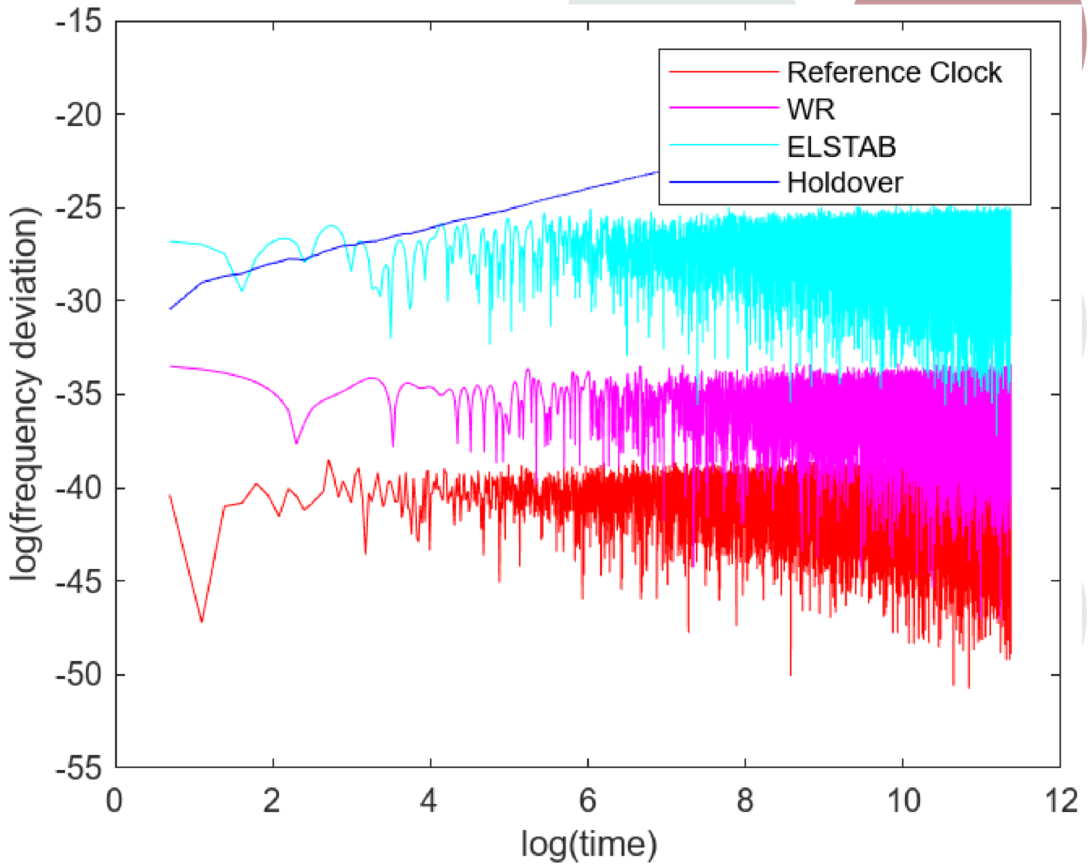


Holdover Mode

T. Włostowski (2010)

G. Hasslinger & O. Hohlfeld (2010)


Holdover
WR
ELSTAB
Reference Clock
log(time deviation)
log(time)
-5
-10
-15
-20
-25
-30
-35
-40
0
2
4
6
8
10
12


Reference Clock
WR
ELSTAB
Holdover
log(frequency deviation)
log(time)
-15
-20
-25
-30
-35
-40
-45
-50
-55
0
2
4
6
8
10
12

Conclusion

The project aim was to develop a simulation of different timing sources and distribution methods.

With the clock and time dissemination simulations I have developed, we can use them to investigate:

- Networks that use different dissemination methods between nodes.
- Observe uncertainties that can arise with each method.
- Observe how uncertainties in timing change as certain connections go down.

What I’ve learnt

The internship was a useful insight in research and development. I’ve learnt how PNT systems function and their importance in telecom networks.

Technical skills I’ve learnt include:

- Conducting research about time sourcing and dissemination.
- Developing mathematical models to simulate timing networks.
- Version controlling my simulations to be used in a collaborative setting.

Soft skills I’ve learnt include:

- Resilience in face of a difficult problem.
- Communicating my simulation models and ideas to my supervisors.