المنظمة العربية للتنمية الصناعية والتقييس والتعدين

التجمّع العربي للمترولوجيا

ARAMET

اللجنة الفنية للزمن والتردّد

الدورة التدريبية الأولى

معايرة أجهزة توليد وقياس التردّد

Frequency counter and synthesizer calibration

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الثلاثاء 3 ديسمبر 2024
الساعة 10:30 صباحا

Plan

1. Fundamental concepts
2. Traceability to S.I
3. Frequency calibration
4. Uncertainty budged
5. Calibration report

Fundamental concepts
-Time-

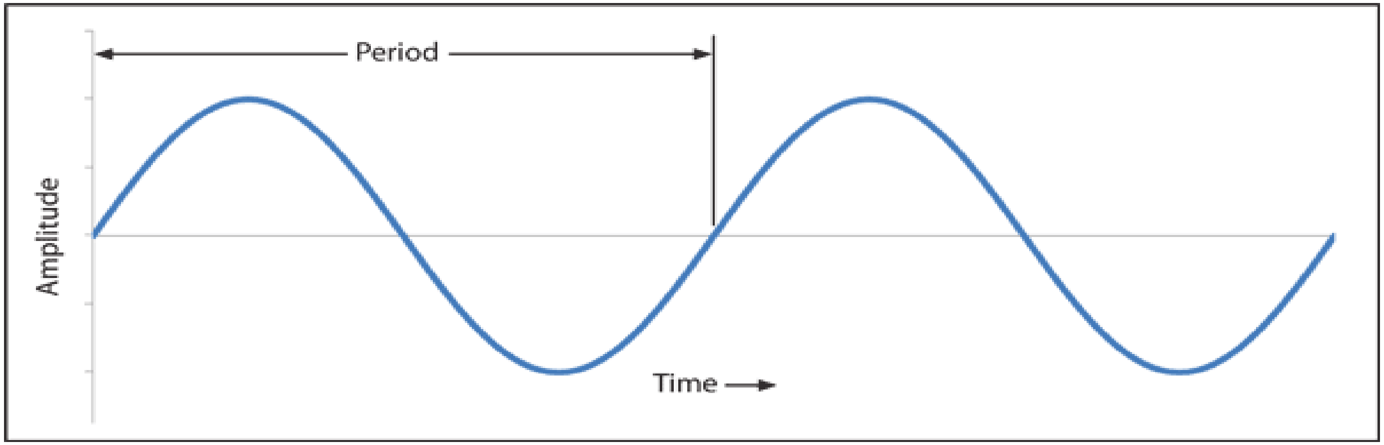
The most asked question for Time in the world is:

What time is it?

Fundamental concepts
-Time-

- **Time** is a measure of an event start to finish.
- **Time** is what we measure in minute, hours, days …

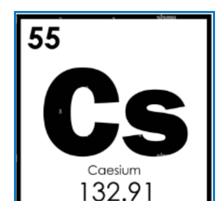
The period is the measured <u>time</u> from when it starts to when it ends (360°).



Fundamental concepts
-Time-

- The official unit of Time is the second
- <u>Second</u> is one of the 7 fundamental units of the international system of units (S.I)
- Second is denoted with the letter "*s*"
- Since 1970, the second has been defined by the atomic frequency of the Cesium 133 atom:

"The duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium 133 atom"



Fundamental concepts
-Time-

Multiples and fractions of "Second"

- 1 minute = 60 second
- 1 hour = 60 minutes
- 1 day = 24 hours
- 1 year = 365,2422 days

Multiple of second (base 60)

- millisecond (ms) = 10^{-3} s
- microsecond (µs) = 10^{-6} s
- nanosecond (ns) = 10^{-9} s
- picosecond (ps) = 10^{-12} s
- femtosecond (fs) = 10^{-15} s

Fractions of second (base 10)

Fundamental concepts
-Frequency-

- **Frequency** (f), of repetitive signals may be defined by the number of cycles of that signal per unit of time. It may be represented by the equation:

$$f = n / t$$

where (n) is the number of cycles of the repetitive signal that occurs in time interval (t).

- If t = 1 second, then the frequency is expressed as (n) cycles per second or (n) Hertz.

Fundamental concepts
-Frequency-

Unit of frequency

- **Frequency is a derived unit from the second**
- **The SI units is (s^{-1})**
- **It's best know by Hz (Hertz)**

Fundamental concepts
-Frequency-

Multiples and fractions of frequency

1 Hertz → 1 Hz

- **Millihertz (mHz): 10^{-3} Hz**
- **Microhertz (µHz): 10^{-6} Hz**

Fractions of frequency (base 10)

- **kilohertz (kHz) = 10^{3} Hz**
- **Megahertz (MHz) = 10^{6} Hz**
- **Gigahertz (GHz) = 10^{9} Hz**

Multiple of frequency (base 10)

Fundamental concepts
-Period & frequency-

Fundamental relation

- **Time and frequency are related**

$$f = 1/t$$

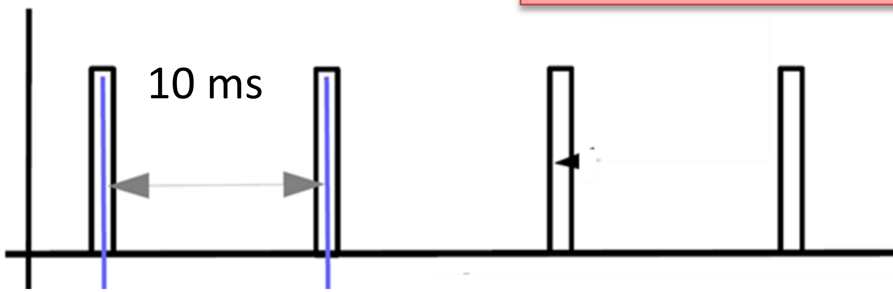
- **The period of a signal is the time between events**

- **The frequency of an event is obtained by counting his occurrences in a time interval (in our case in a second)**

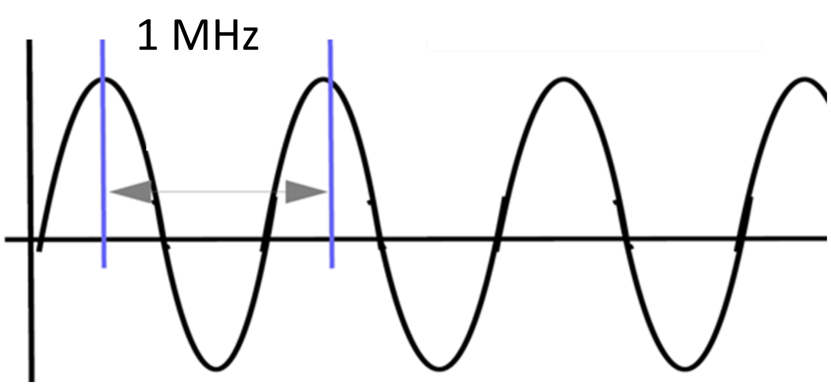
Fundamental concepts
-Period & frequency relation-

Example:

Fundamental relation



Repetitive pulse with 10 ms of period.
→Frequency = 1/10ms=100 Hz



Repetitive sinus with 1 MHz of frequency
→ Period= 1 µs

Fundamental concepts
“Frequency offset”

Frequency offset is a measure of how closely an oscillator:

- Produces its **nameplate** (nominal) frequency,
- **How well** an oscillator is **adjusted**.

→ Frequency offset also called **frequency Accuracy**

→It doesn't tell us about the Quality of an oscillator.

Fundamental concepts
“Frequency offset”

Frequency offset (f_{off}) is also called:

- ❖ **The relative frequency error**
- ❖ **The fractional frequency**
- ❖ **The frequency deviation**

$$f_{off} = \frac{f_{measured} - f_{nominal}}{f_{nominal}} = \frac{\Delta f}{f}$$

Hz/Hz
or without
unit

Fundamental concepts
"Time offset"

Time offset (t_{off}) is called:

- **The relative time error**
- **The fractional time**
- **The time deviation**

s/s
without unit

$$\frac{\Delta t}{T} = \frac{t2 - t1}{T}$$

Time interval difference

Time observation

Fundamental concepts
-Time and frequency deviation-

Fundamental relation

Frequency difference
$f_{MEASURED} - f_{REFERENCE}$

Frequency Reference
$f_{REFERENCE}$

$$\frac{\boxed{\Delta f}}{\boxed{f}} = -\frac{\boxed{\Delta t}}{\boxed{T}}$$

Time interval difference
$t_2 - t_1$

Time interval
(observation time)

Fundamental concepts
-Time and frequency deviation-

Demonstration

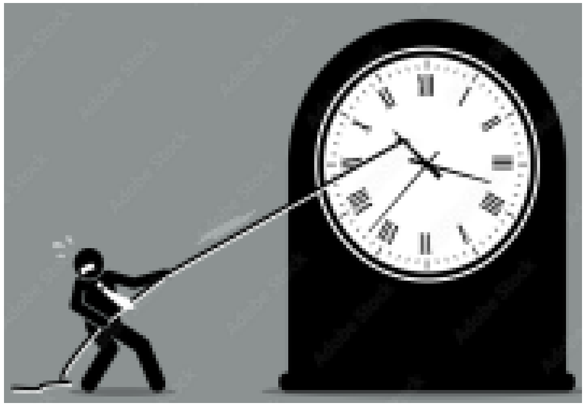
$$f_{off} = \Delta(f)/f$$
$$= \Delta(1/T) \,/\, (1/T)$$
$$= -(\Delta t/T^2) \times T$$
$$= -\,\Delta t/T$$

$$\frac{\boxed{\Delta f}}{\boxed{f}} = -\frac{\boxed{\Delta t}}{\boxed{T}}$$

Fundamental concepts
-Time and frequency deviation-

- $f_{off} = \dfrac{\Delta f}{f} > 0 \rightarrow \dfrac{\Delta t}{T} < 0$

→ **time deviation is (-) and the clock runs slower than the reference ($t_2 < t_1$)**



Fundamental concepts
-Time and frequency deviation-

- $f_{off} = \dfrac{\Delta f}{f} < 0 \rightarrow \dfrac{\Delta t}{T} > 0$

$\rightarrow$ **time deviation is (+) and the clock runs faster than the reference ($t_2 > t_1$)**

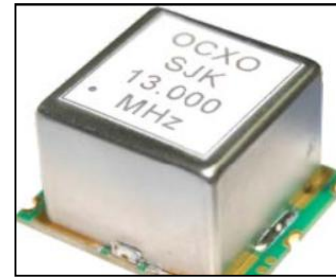
Fundamental concepts
-Quartz oscillators-

Most equipment in time and frequency metrology have an internal quartz oscillator.

An quartz oscillator is a device that produce a periodic signal.

The nominal frequency can vary from device to other.

1 MHz- 5 MHz-10 MHz-13 MHz



Fundamental concepts
-Clock-

- A <u>clock</u> is an ensemble of an oscillator and an counter mechanism.

Oscillator **clock**

Fundamental concepts
-Clock drift-

Some examples

Oscillator 1

Frequency offset $f_{off}=\Delta f/f=$ 5E-07 Hz/Hz = 5E-07

→ $\Delta t/T=-\Delta f/f=$ - 5E-07 s/s = - 5E-07

→In one hour (T=3600 s), the oscillator will drift:
-5E-07×(3600) =-1.8 ms/hour

Fundamental concepts
-Clock drift-

Some examples

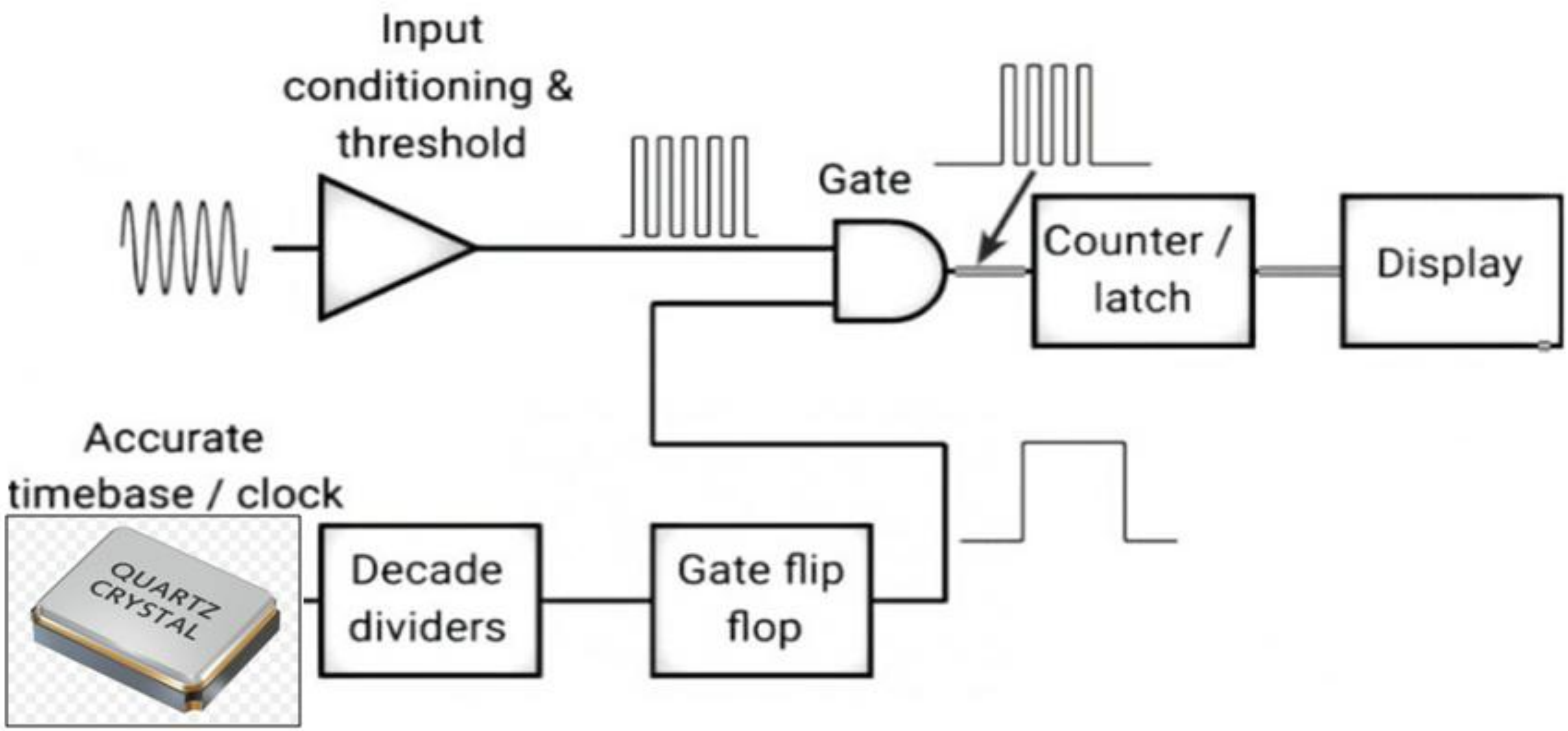
Oscillator 2: The oscillator had one microsecond (1 µs) phase change (slower (-) than the reference) in one day (86400 s)

→ $f_{off}=\Delta f/f=-\Delta t/T=-(-0.000001)/86400$

→ $f_{off}=\Delta f/f=1.15\times10^{-11}$

Fundamental concepts
-Frequency counter-

- A **frequency counter** is ensemble of an oscillator and an electronic functions to calculate the desired frequency.



Fundamental concepts
“Quartz oscillators access”

Frequency counter

Quality of oscillator

External **Ref IN**

Internal **Ref OUT**

Fundamental concepts
"Quartz oscillators access"

Synthesizer

External Ref IN

Internal Ref OUT

Fundamental concepts
-Synchronisation-

Synchronization is a term used to say that two or more devices have the **same time**:

Example:

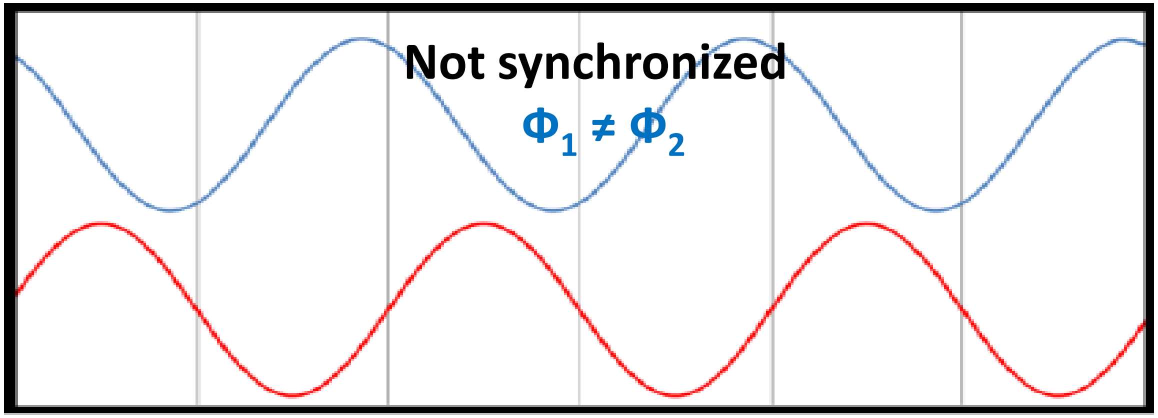
- Clock
- Time interval counter
- Telecommunication system…

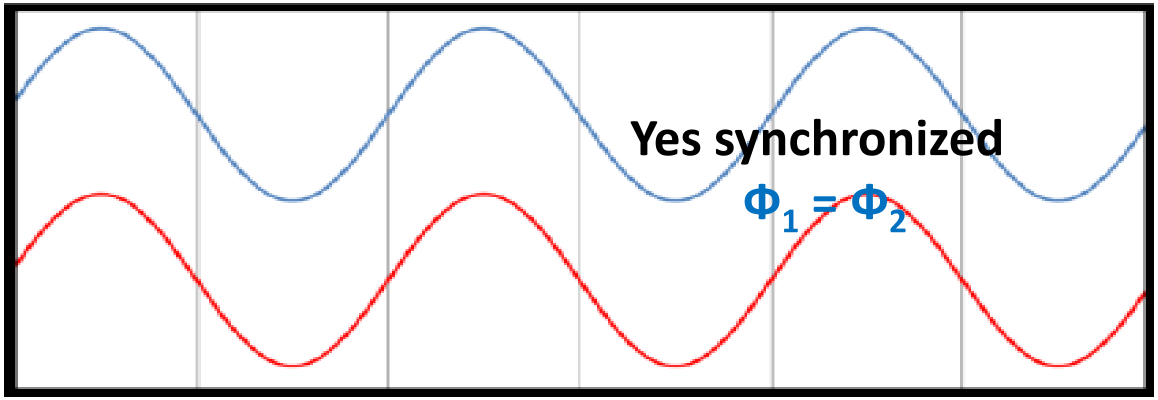
Fundamental concepts
-Synchronisation-

Example of Synchronization (time)

$S_1(t)=A.Sin(2\pi.f_1.t+\Phi_1)$

$S_2(t)=B.Sin(2\pi.f_2.t+\Phi_2)$





We suppose that $f_1=f_2$

Fundamental concepts
-Syntonization-

Syntonization is a term used to say that two or more devices have the **same frequency**:

Example:

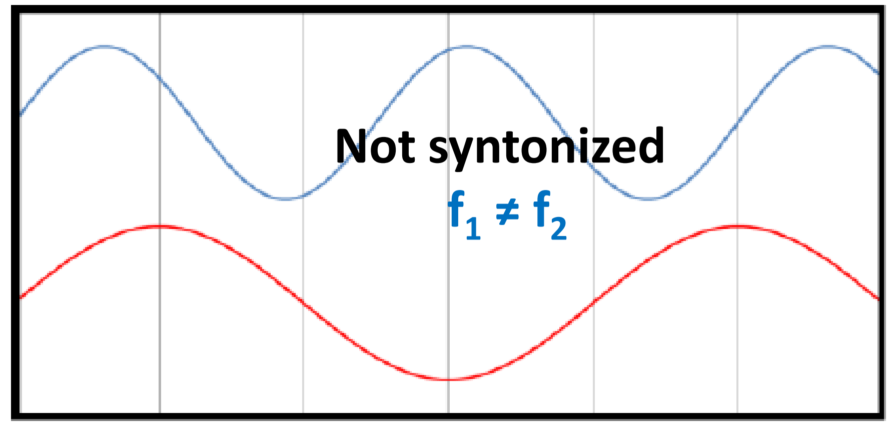
- Oscillator
- GPSDO
- Radio frequency counter…

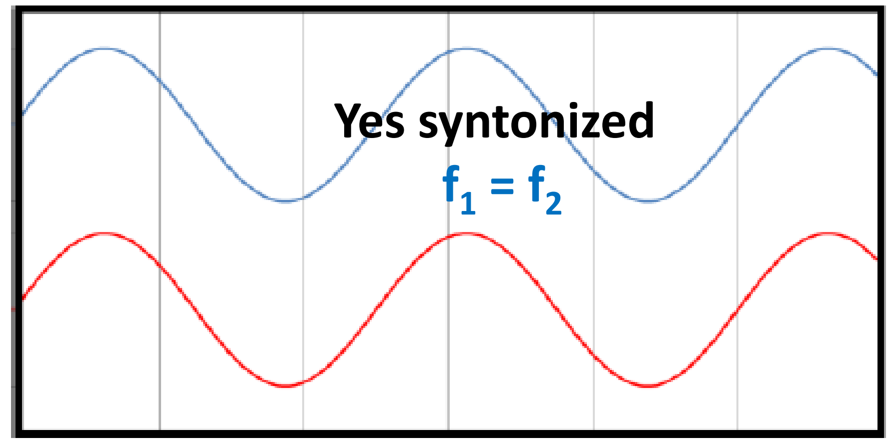
Fundamental concepts
-Syntonization-

Example of Syntonization (frequency)

$S_1(t)=A.Sin(2\pi.f_1.t+ \Phi_1)$

$S_2(t)=B.Sin(2\pi.f_2.t+ \Phi_2)$





Φ_1 and Φ_2 are not necessary equals

Fundamental concepts
-Time and frequency domain-

We have two forms to analyze the systems:

Time domain: indicates that we analyze mathematically the signal in **time** terms

→Oscilloscope, frequency counter…

y=function(t)

Frequency domain: indicates that we analyze mathematically the signal in **frequency** terms

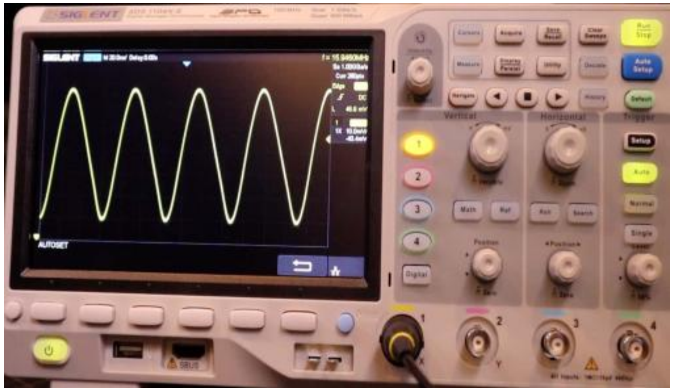
→ Spectrum analyzer

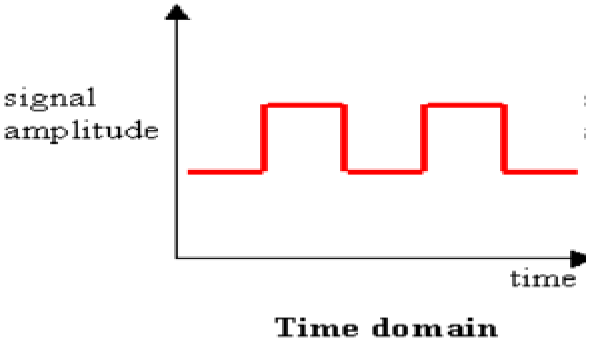
Y=function(f)

Fundamental concepts
-Time and frequency domain-

Example of Time domain

- Voltage and power is measured in function of time





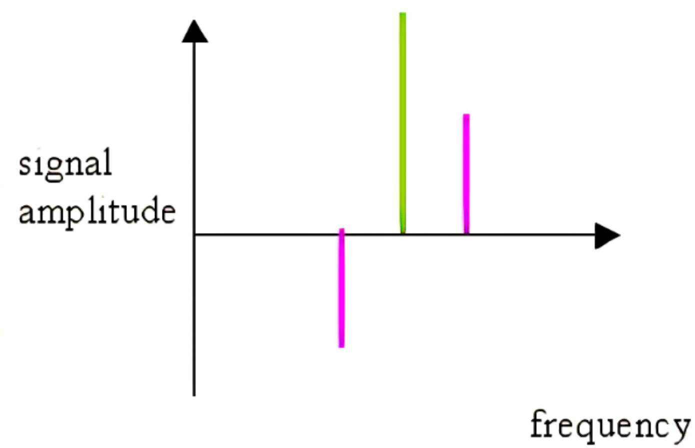
- Time interval counters and oscilloscopes are typically used.

Fundamental concepts
-Time and frequency domain-

Example of frequency domain

Voltage and power is measured in function of the frequency (f)

Spectrum analyzers are typically used in frequency domain



Fundamental concepts
-Measurement equipment-

Frequency counter

Spectrum Analyser

Oscilloscope

Parameters to be measured:
-Frequency (f)
-Time interval (t)
-Pulse width (s)
-Rise /fall time (s)
-Time …

Stopwatch (s)

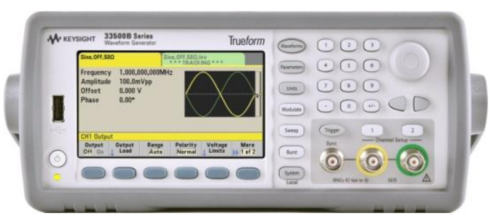
Tachometer(rpm)

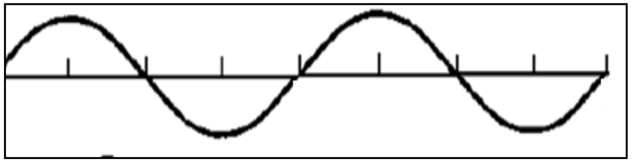
Fundamental concepts
-Frequency source-

- **Frequency source (synthesizer/generator)**

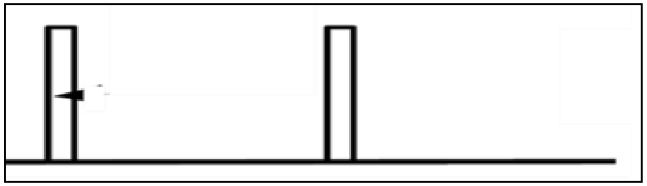
Calibrator source

Waveform generator

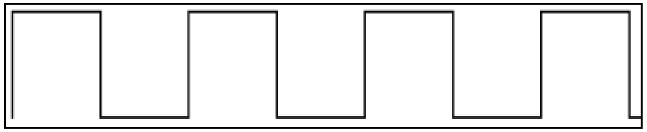




sine



Pulse



Square

Fundamental concepts
-Frequency Standard-

Reference in time and frequency

<u>Quartz</u> D.O

<u>Rubidium</u> clock D.O

<u>Hydrogen</u> Maser

<u>Cesium</u> clock

Fundamental concepts
-Frequency Standard-

The typical reference oscillators are:

- ❑ Quartz oscillators

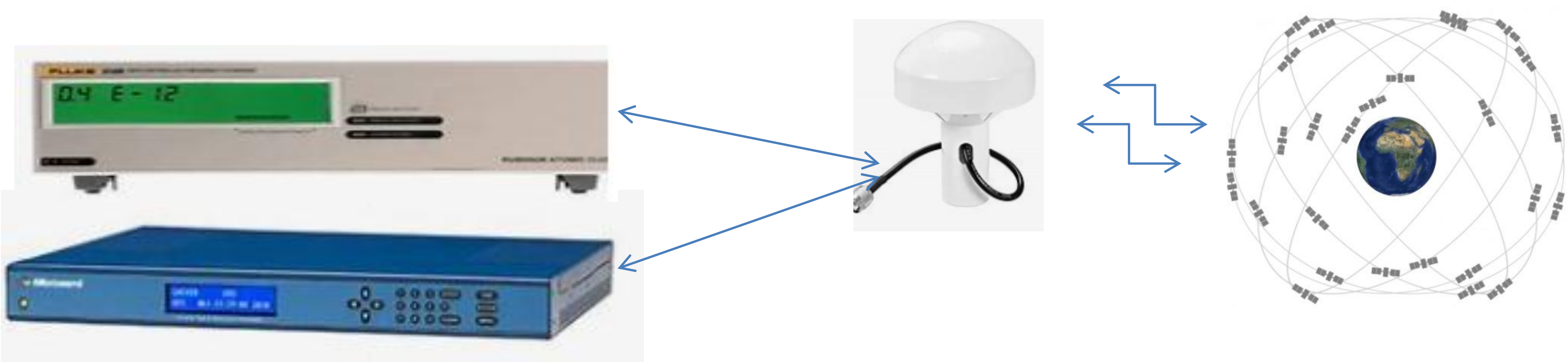
- ❑ Rubidium oscillators

- ❑ Cesium oscillators

- ❑ GPS Disciplined Oscillators

Fundamental concepts
-Frequency Standard-

- They are local oscillators disciplined (periodically corrected) by signals from the GPS satellite network

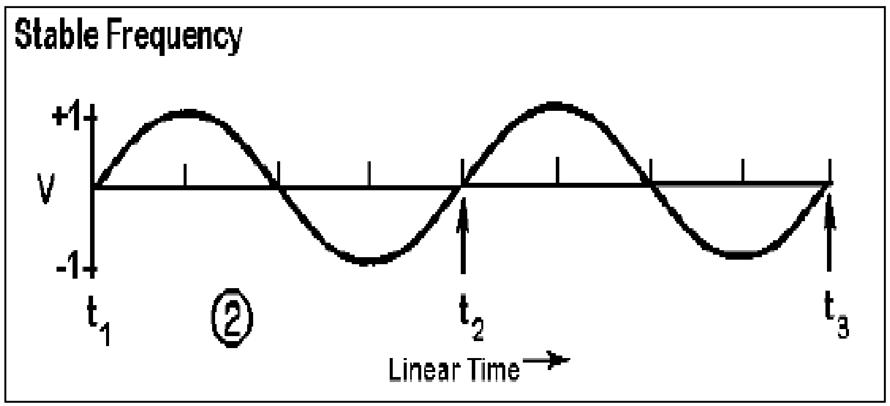


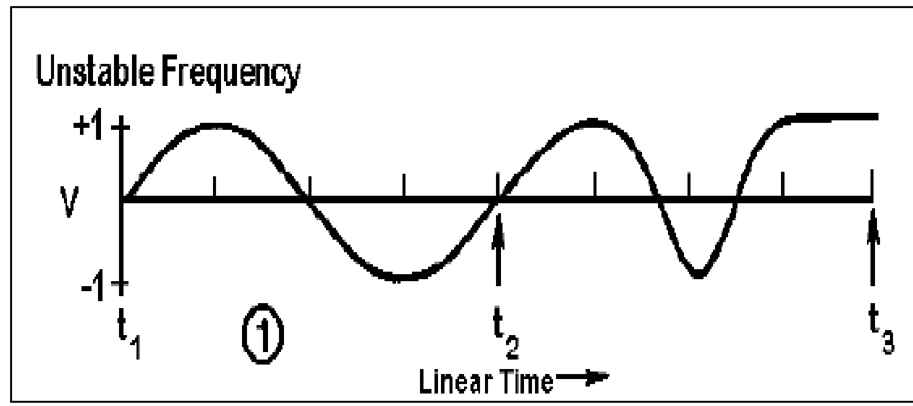
- The short term stability depends on the local oscillator (quartz, rubidium, etc.) and the long term stability depend on the GPS signals

Fundamental concepts
-Stability-

In Time and Frequency metrology, **the stability** of an oscillator is its most important characteristic.

Stability shows how the output frequency changes over time.





Fundamental concepts

-Accuracy-

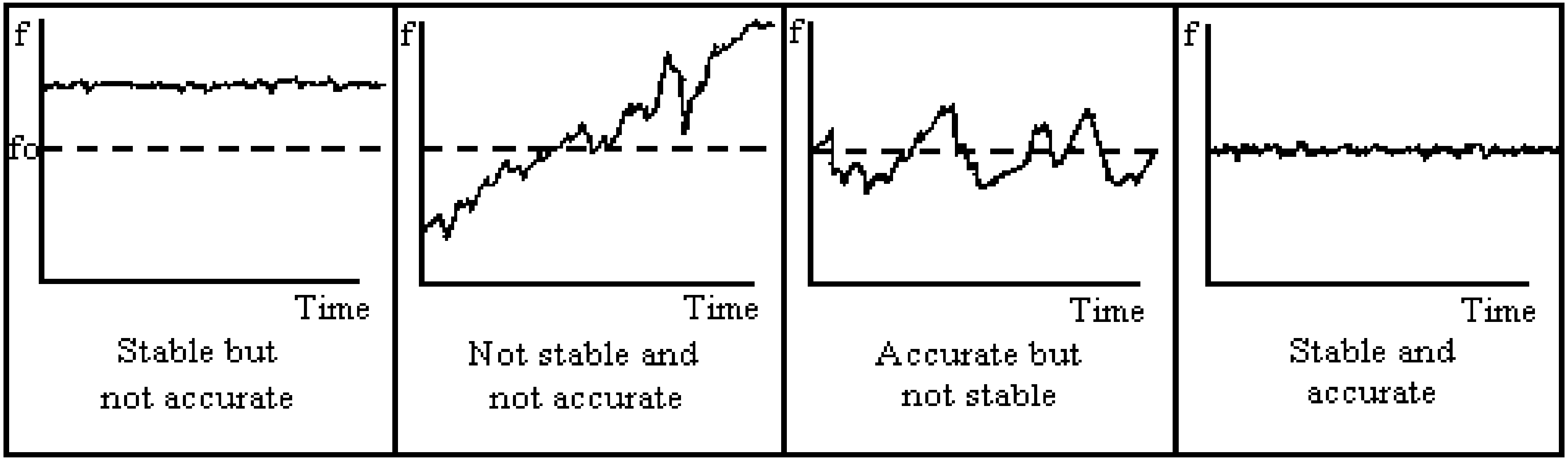
Accuracy shows how the output frequency is close to the nominal frequency.

Frequency offset (f_{off} =Δf/f) gives us an idea about the accuracy of frequency.

$$\Delta f/f=(f_x-f_N)/F_N$$

Fundamental concepts

-Stability vs Accuracy-



Fundamental concepts
-Stability computation-

How to calculate stability?

To evaluate the stability of a frequency, you should calculate the Allan deviation formula.

1- Take a (N) frequency measurement f_i with your calibrated frequency counter

2- f_i and f_{i+1} should be spaced by a time τ (time of observation)

3- Calculate the formula of Allan deviation $\sigma(\tau,2)$

Fundamental concepts
-Stability computation-

Allan deviation

- It’s a statistic used to estimate frequency stability

- It was named after David Allan, a physicist who retired from NIST in 1993

- The variances is called Allan Variance (AVAR, σ_y^2)
- The deviation is called Allan Deviation (ADEV, σ_y)

$$AVAR=(ADEV)^2$$

Fundamental concepts
-Stability computation-

How to calculate stability ?

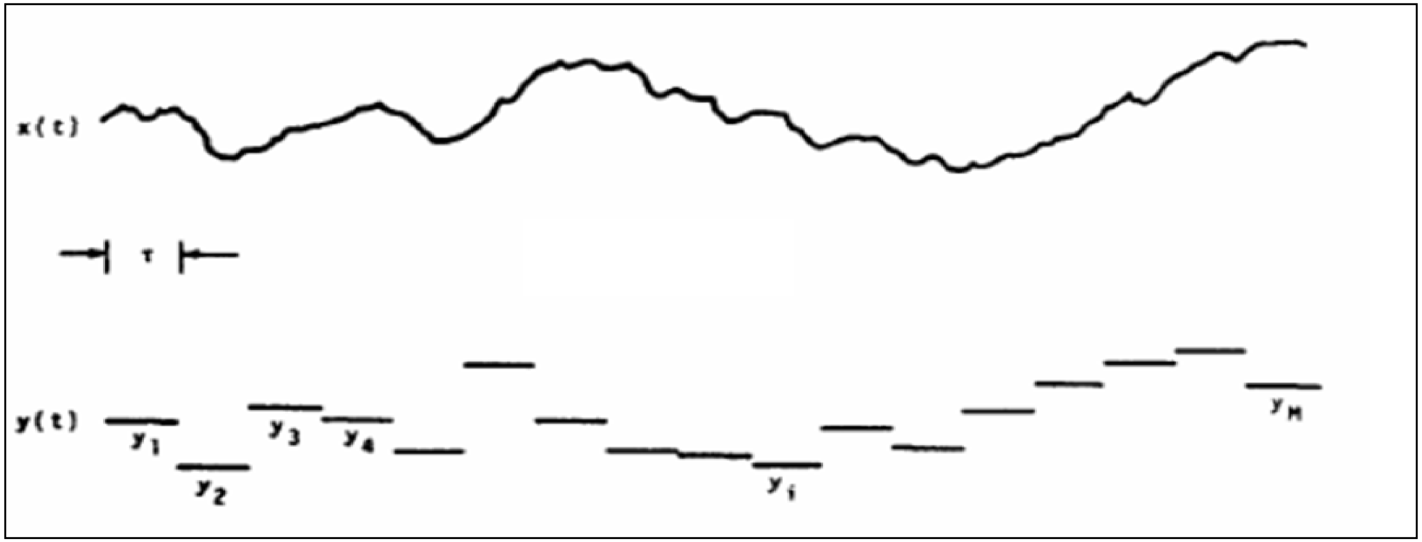
- The ADEV is computed by taking the difference between successive pairs of data points (f_{i+1}-f_i) to remove the trend (slope) contributed by the frequency offset.

- This is necessary because by removing the trend, we can make the data converge to a mean.

- ADEV is only useful for computing stability, and not for accuracy.

Fundamental concepts
-Stability computation-

Calculate the fractional frequency y(i)



Fractional frequency $$y(i) = \frac{f_x - f_N}{f_N}$$

Fundamental concepts
-Stability computation-

Allan deviation of frequency (1)

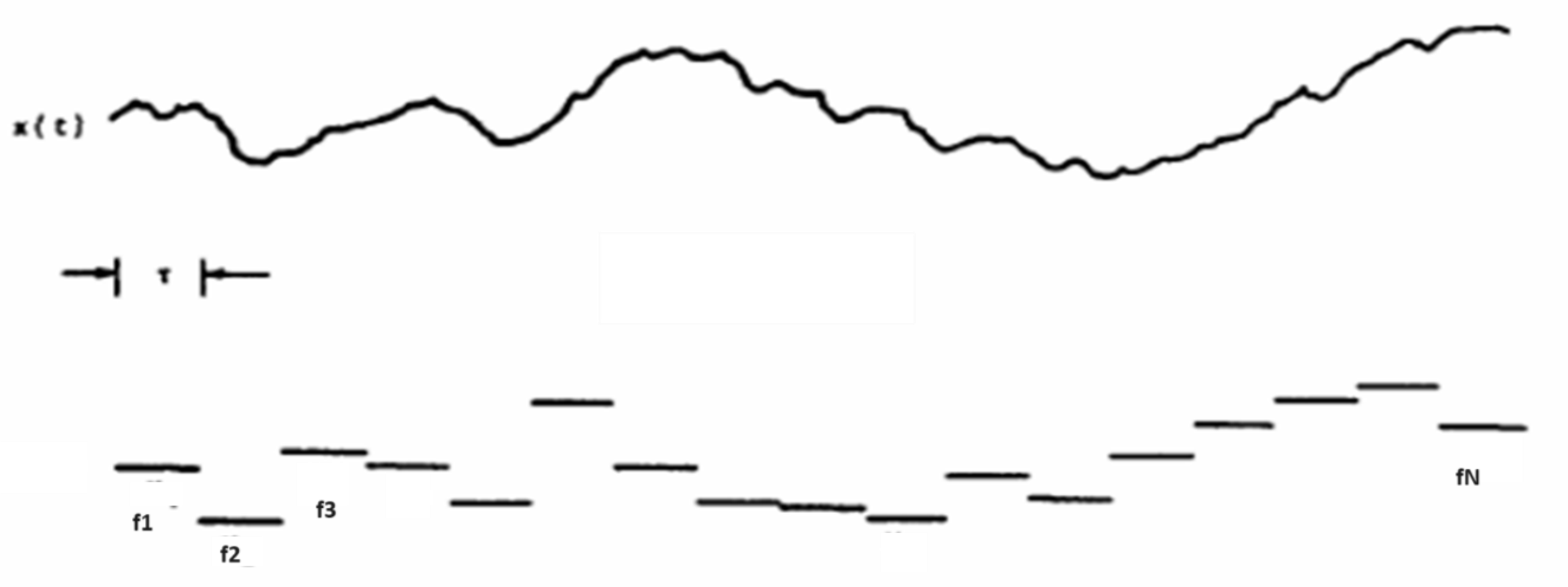
$$\sigma(\tau,2)=\sqrt{\frac{1}{2(N-1)}\sum_{i=1}^{N-1}(y_{i+1}-y_i)^2}$$

Without unit
Hz/Hz

- **σ: Allan Deviation of frequency**
- **τ: Observation time (s)**
- **N: Number of samples**
- **y_i: Frequency offset**

Fundamental concepts
-Stability computation-

Allan deviation of frequency (2)



$$\sigma(\tau,2)=\sqrt{\frac{1}{2(N-1)}\sum_{i=1}^{N-1}(f_{i+1}-f_i)^2}$$

Hz

Fundamental concepts
-Stability computation-

Example:

Time of observation τ=10 s

Frequency fi (Hz)	$(f_{i+1}-f_i)^2$	$\sigma(\tau)$	Uncertainty $\sigma/\mathrm{sqrt}(N)$
10000000,025	1,3E-02	1.74×10^{-1} Hz	**5.51×10^{-2} Hz**
10000000,137	4,7E-02		
10000000,354	8,3E-02		
10000000,642	1,6E-01		
10000000,244	6,6E-03		
10000000,325	2,6E-02		**5.51×10^{-9}**
10000000,485	5,3E-02		
10000000,254	9,0E-06		
10000000,251	1,6E-01		
10000000,650	***		

Fundamental concepts
-Accuracy Computation-

Example 2 :

$f_{off}=\Delta f/f= 5E\text{-}07$

For the frequency 10 MHz

$\rightarrow \Delta f=f_x-f_N= (5E\text{-}07) \times 10^7 = 5$ Hz

$\rightarrow f_x=\Delta f+ f_N=$10 000 000 Hz+ 5 Hz= 10 000 005 Hz (exactly)

Fundamental concepts
-Accuracy Computation-

Example 1:

$\Delta t/T=-1.97\times10^{-13}$

$\rightarrow \Delta f/f=-\ \Delta t/T= 1.97\times10^{-13}$

$\rightarrow \Delta f/f=(f_x-f_N)/f_N$

$\rightarrow fx= f_N \times(1+ \Delta f/f)$ $\quad$ f_x=9 999 999,99999802 Hz

Traceability to S.I

- The official primary source of traceability is the Key comparison that defines UTC (CCTF-k001.UTC)
- To obtain the time difference between your local time UTC(k) and UTC, you have the "Circular T" Document published by BIPM (Monthly & Weekly)
- To participate in the comparison, you need at least one frequency standard (Cesium clocks 5071A), a Time Transfer System (TTS 4-5, PolaRx5TR…) and Antenna (GPS, GALILEO, WAAS, GLONASS…)

Traceability to S.I

Circulaire T - BIPM

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CIRCULAR T 442                                                                  ISSN 1143-1393
2024 NOVEMBER 13, 14h UTC
                          BUREAU INTERNATIONAL DES POIDS ET MESURES
                THE INTERGOVERNMENTAL ORGANIZATION ESTABLISHED BY THE METRE CONVENTION
             PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX  TEL. +33 1 45 07 70 70 tai@bipm.org
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The contents of the sections of BIPM Circular T are fully described in the document "Explanatory supplement to BIPM Circul
available at https://webtai.bipm.org/ftp/pub/tai/other-products/notes/explanatory_supplement_v0.8.pdf

1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties.
From 2017 January 1, 0h UTC, TAI-UTC = 37 s.

Date 2024 0h UTC	SEP 26	OCT 1	OCT 6	OCT 11	OCT 16	OCT 21	OCT 26	OCT 31	Uncertainty/ns			Notes
MJD	60579	60584	60589	60594	60599	60604	60609	60614	uA	uB	u	
Laboratory k				[UTC-UTC(k)]/ns								
AGGO (La Plata)	599.7	592.6	595.3	591.1	574.9	558.5	555.4	560.9	0.7	2.9	3.0	
AOS (Borowiec)	-10.7	-9.8	-8.4	-7.0	-4.6	-3.7	-2.2	-1.0	0.3	3.5	3.5	
APL (Laurel)	0.3	-1.3	-1.6	-2.0	-2.8	-2.1	-2.8	-3.7	0.3	NC	-	
AUS (Sydney)	-26.0	-27.9	-19.5	-5.8	-12.2	9.2	17.5	17.6	0.3	2.9	2.9	
BEV (Wien)	-45.1	-21.8	-5.2	0.2	14.3	18.9	31.1	33.7	0.3	2.9	2.9	(1)
BFKH (Budapest)	12109.8	12157.9	12202.0	12244.4	12298.3	12343.8	12387.8	12428.6	1.5	7.2	7.4	
BIM (Sofiya)	1885.8	1933.4	1981.6	2020.7	2067.5	2117.7	2162.3	2208.6	0.3	2.6	2.6	
BIRM (Beijing)	-2.5	-1.4	-0.7	0.5	-2.6	-0.3	-2.4	-3.2	0.3	3.4	3.4	
BSJ (Kingston)	32.0	22.5	26.1	25.1	4.7	19.9	11.1	15.5	7.0	7.0	9.9	
BY (Minsk)	-4.2	-4.6	-3.4	-4.6	-4.2	-3.5	-2.6	-3.1	1.5	3.0	3.3	
CAO (Cagliari)	-16170.6	-16291.1	-16410.8	-16532.6	-16645.1	-16755.8	-16875.1	-16993.5	0.7	NC	-	
CH (Bern-Wabern)	-1.9	-4.1	-4.1	-3.8	-2.7	-1.8	-0.2	1.2	0.5	1.0	1.1	(2)
CNES (Toulouse)	-1.8	-4.6	-2.5	1.1	1.0	0.2	-0.3	0.3	0.3	3.0	3.0	
CNM (Queretaro)	-4.2	-3.5	-6.4	-5.0	-7.1	-4.8	-3.5	-4.8	3.0	4.3	5.2	
CNMP (Panama)	-3.6	-0.5	2.7	-5.4	-0.5	2.0	0.6	-6.5	0.3	5.5	5.5	
DFM (Horsholm)	3.5	4.3	4.8	5.4	6.3	5.4	-	-	0.3	2.7	2.7	
DFNT (Tunis)	-5235.1	-5309.6	-5395.1	-5497.4	-5599.4	-5674.5	-5758.7	-5859.8	0.7	2.6	2.7	
DMDM (Belgrade)	-2.6	-5.6	-0.9	-5.1	-4.4	-3.3	-3.4	-10.1	0.3	3.9	3.9	
DTAG (Frankfurt/M)	26.4	31.2	43.6	49.0	46.6	55.6	56.7	61.9	0.3	3.4	3.4	
ESA (Noordwijk)	2.2	2.5	3.4	3.4	2.9	2.2	1.9	1.7	0.3	2.7	2.7	

Traceability to S.I

Clock Drift

MONTHLY RATES OF TAI-CLOCK (CONT.)

LAB.	CLOCK	60459	60489	60519	60549	60579	60614
CNMP	36 1806	-2.22	-1.54	-5.36	-3.63	-3.68	-2.40
CNMP	36 1752	-1.18	-1.37	-1.54	0.32	0.16	-0.26
CNMP	36 2873	2.63	1.79	3.46	3.16	4.10	4.02
CNMP	36 3179	-18.16	-18.10	-18.48	-19.00	-17.06	-18.15
CNMP	36 3162	0.00	0.00	6.43	5.50	6.81	5.24
DFNT	36 5047	-19.29	-18.03	-17.62	-18.09	-18.12	-17.85
DFNT	36 1811	19.94	20.56	20.55	21.25	19.62	20.08
DMDM	35 2191	-1.26	-0.60	1.01	3.68	2.44	1.68
DMDM	36 2033	-57.56	-57.71	-58.05	-58.44	-58.73	-56.77
DTAG	35 2966	0.24	0.13	0.41	1.27	1.84	0.99
DTAG	35 2635	1.02	1.28	2.26	3.19	2.46	2.76
DTAG	35 136	-0.93	-0.59	-0.73	0.44	1.08	1.01
ESA	35 2353	6.58	7.07	7.23	6.55	6.57	6.97
ESA	41 1033	-145.08	-145.56	-146.54	-146.87	-147.09	-147.26
ESA	35 2210	18.20	18.85	18.28	18.78	18.75	18.61
ESA	35 2025	3.37	3.08	3.77	4.17	4.94	4.60
ESA	35 1615	-5.74	-5.54	-5.30	-5.06	-4.96	-5.62
ESA	40 2544	-6.75	-6.76	-6.99	-7.20	-7.37	-7.33
ESA	40 2551	-27.67	-27.99	-28.48	-28.85	-29.20	-29.92
HKO	35 4233	1.84	2.77	3.89	2.94	3.51	4.41
HKO	35 5122	0.00	0.00	0.00	1.39	1.70	2.00
IBM	36 3397	0.00	0.00	0.00	0.00	0.00	0.89
ICE	36 3159	4.86	1.48	2.55	2.58	4.92	3.12
ICE	36 3522	5.30	-3.64	-0.08	0.02	6.20	-0.13
IFAG	36 1167	-3.62	-3.70	-3.49	-3.55	-3.72	-2.15
IFAG	36 1173	-1.21	-0.86	-3.36	-4.38	-3.71	-0.96
IFAG	36 1732	11.45	12.03	12.22	11.56	12.05	11.68
IFAG	36 1798	-8.72	-7.58	-7.90	-8.52	-7.46	-7.51
IFAG	40 4418	-13.26	-13.79	-14.22	-14.66	-15.47	-15.93
IFZG	35 4701	-0.67	0.19	-0.70	0.12	-0.06	0.09

Traceability to S.I

Key comparaison CCTF-K00.1.UTC

BUREAU INTERNATIONAL DES POIDS ET MESURES

Key comparison CCTF-K001.UTC - Results
Degrees of equivalence D_k = [UTC - $UTC(k)$] for August 2024
Computed 2024 SEPTEMBER 11, 09h UTC

Coordinated Universal Time UTC and its local realizations UTC(k) in National Metrology Institutes and Designated In
Computed values of [UTC - $UTC(k)$] and uncertainties valid for the period of this publication

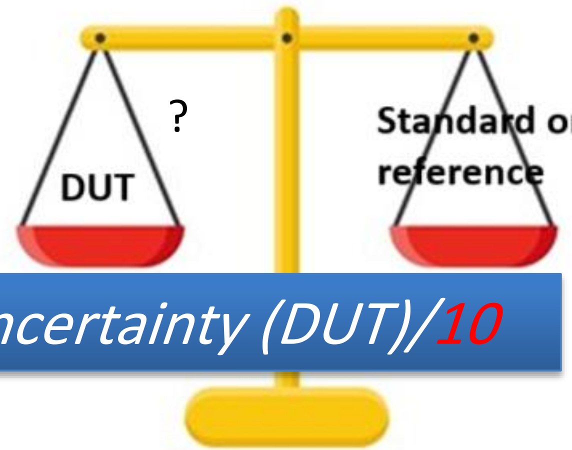
Date 2024 0h UTC	AUG 2	AUG 7	AUG 12	AUG 17	AUG 22	AUG 27	Uncertainty/ns		
MJD	60524	60529	60534	60539	60544	60549			
Laboratory k			[UTC - $UTC(k)$]/ns				U_a	U_b	U_k
BelGIM	-0.9	-0.4	-1.1	-0.3	-0.7	-0.6	3.0	6.0	6.6
BEV	-27.2	-28.7	-27.8	-31.7	-36.5	-32.4	0.4	5.6	5.6
BFKH	11551.2	11594.5	11649.1	11702.7	11755.2	11814.5	1.4	14.2	14.2
BIM	1347.3	1401.0	1448.5	1500.2	1548.2	1597.0	0.4	5.2	5.2
BMM	1898.3	1934.8	1944.5	1956.6	1977.1	2001.2	0.4	5.6	5.6
BSJ	12.2	26.5	37.8	40.2	33.5	30.6	14.0	14.0	19.8
CENAM	2.2	5.2	0.4	-2.7	-6.4	-1.4	6.0	8.6	10.4
CENAMAP AIP	-2.5	-0.4	3.3	-3.1	-1.6	2.2	0.4	11.0	11.0
DEF-NAT	-4226.3	-4310.7	-4395.2	-4497.6	-4602.9	-4691.4	1.4	5.2	5.4
DFM	4.5	5.5	6.4	7.9	8.2	9.3	0.4	5.4	5.4
DZM	33.2	35.8	40.7	46.7	52.6	51.2	0.4	5.2	5.2
EMI									

Frequency Calibration

- **Frequency calibration measure the performance of frequency standards**
- **The frequency standard being calibrated is called the *device under test (DUT)***
- **DUT can be any devices in time&frequency domain like**
  - ***Quartz***
  - ***Rubidium***
  - ***Cesium oscillator***

Frequency Calibration

➢ **To perform the calibration, the DUT must be compared to a *standard or reference.***



Uncertainty (reference) ≤ uncertainty (DUT)/10

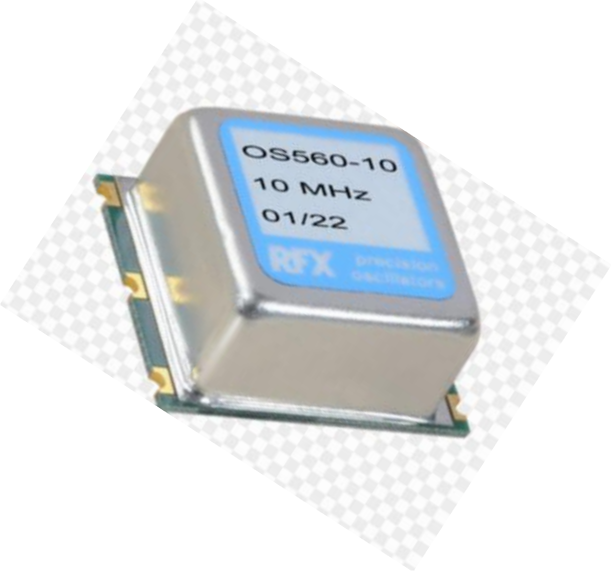
➢ ***The calibration is valid when the reference outperform the DUT at least by a ratio of 10.***

Example: U(DUT)=10^{-9} → U(reference) <=10^{-10}

Frequency Calibration

➢ **Once the calibration is completed, the metrologist should be able to state how close the DUT's output is to its *nameplate frequency:***

$$\Delta f = f_x - f_N$$



Example: $F_N = 10\ \text{MHz}$

$fx = 10\ 000\ 000.03\ \text{Hz}$

$\rightarrow \Delta f = f_x - f_N = 0.03\ \text{Hz}$

Frequency Calibration

- **The reference used for the calibration must be *traceable.***
- ***To be traceable to S.I, an unbroken chain should be realized:***

1- You can obtain your traceability from BIPM Circular T publication for your UTC(lab);

2- You can use transfer standards to deliver a frequency reference. In this case, this reference must be periodic calibrated in an other laboratory (traceable to S.I)

Frequency Calibration

- **Once a traceability is in place, the next step is developing the technical procedure used to make the calibration. This procedure is called the *calibration method.***

- ***The laboratory can*** **automate the frequency calibration process (computer+ software+ data cable)**

Frequency Calibration

-Frequency Standards-

Frequency standards have an internal device that produces a periodic, repetitive event called Resonator

Resonator + Driven energy = Oscillator

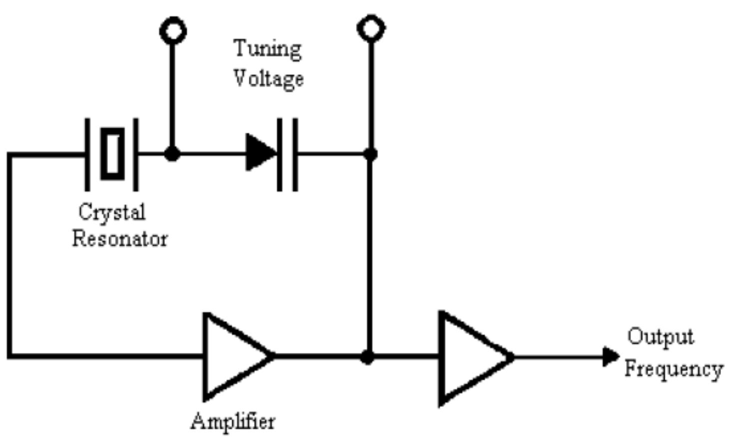
Two main types of oscillators are used as frequency standards:

- Quartz oscillators
- Atomic oscillators

Frequency Calibration
-Frequency Standards-

1- Quartz oscillators

They are sensitive to environmental parameters such as temperature, humidity, pressure, and vibration.



- The *Oven-Controlled crystal oscillator (OCXO)*
- The *Temperature-Compensated crystal oscillator (TCXO).*
- *The microcomputer-compensated crystal oscillator (MCXO)*

Frequency Calibration
-Frequency Standards-

2- Atomic Oscillators

Atomic oscillators use the quantized energy levels in atoms and molecules as the source of their resonance frequency:

- ✓ Rubidium Oscillators (^{37}Rb)
- ✓ Cesium Oscillators (^{133}Cs)
- ✓ Hydrogen Masers (^{1}H)

Fundamental concepts
-Comparative table-

Parameter	Quartz OCXO	Rubidium	Cesium	GPSDO
Life expectancy	Depend of the electronic (more than 10 years)	10 to 25 years	5 to 10 years	Depend of the electronic (more than 10 years)
Frequency accuracy after 30 minute warm-up	No guaranteed accuracy, must be set on frequency	5×10^{-10}	1×10^{-12}	1×10^{-12}
Stability at 1 s	1×10^{-12}	1×10^{-11}	1×10^{-11}	Parts in 10^{10}
Stability at 1 day	1×10^{-10}	2×10^{-12}	1×10^{-13}	2×10^{-13}
Stability at 1 month	Parts in 10^{9}	5×10^{-11}	Parts in 10^{14}	Parts in 10^{15}
Noise floor	≤ 10 s	≤ 1 000 s	Several days to 30 days	The noise is always down because of the frequency correction to agree with UTC
Aging	1×10^{-10} / day	5×10^{-11}/month	None, by definition	None, frequency is corrected by satellites
Cost (USD, in USA)	\$200 to \$2000	\$1000 to \$8000	\$35000 to \$75000	\$1000 to \$15000

Frequency Calibration
-Parts-

- **Calibration is formed by 4 parts**

  - **The Device Under Test (DUT)**



It can be a device <u>to generate </u>or <u>to measure</u>

  - **The calibration reference**

It's the source of traceability. It can be:



Frequency Calibration
-Parts-

The calibration method

It's important to determine the method to use to ensure the quality of your result and the repeatability of experiment.

The calibration method is directly in relation with DUT, the reference and how to acquire Data;

Frequency Calibration
-Parts-

The calibration method

For this DUT (oscillator based in)	Recommended reference
Quartz	Rubidium Cesium GPSDO ***National Standard***
Rubidium	Cesium GPSDO ***National Standard***
Cesium	GPSDO, allow at least 1 week or maybe longer, for the calibration ***National Standard***
GPSDO	Normally not calibrated unless a ***National Standard*** is used.

Frequency Calibration

-Parts-

The calibration method

Devices under Test (D.U.T)	Recommended method
-Synthesizer -Frequency counter -Waveform and signal generators -Any devices that display signal and has an signal output …	Direct frequency (f)
Quartz oscillator Frequency counter -Waveform and signal generators -Any devices that display signal and has an signal output …	Direct phase → $\boxed{\frac{\Delta f}{f}} = -\boxed{\frac{\Delta t}{T}}$

Frequency Calibration

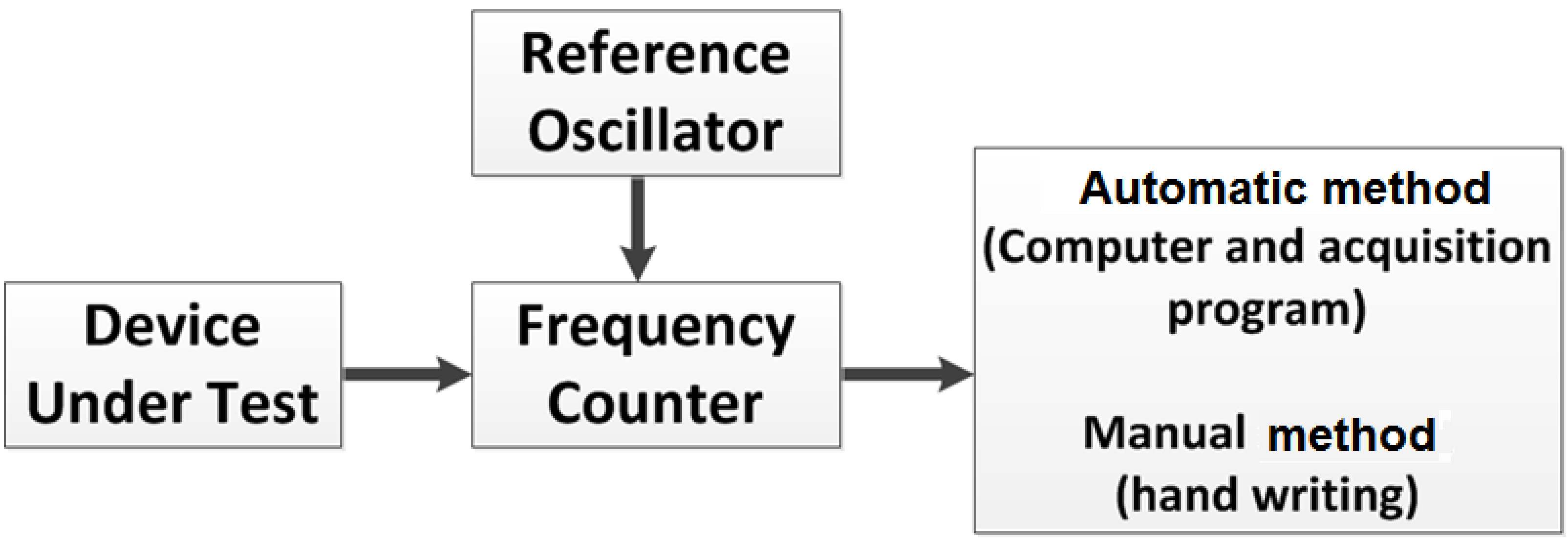
-Parts -

The calibration method

Devices under Test (D.U.T)	Recommended method
-Stopwatches, mechanical clocks, quartz oscillators and atomic oscillators	Time interval (T.I.C)

The calibration method

You can acquire directly the frequency by using a frequency counter.



Frequency Calibration
-Parts -

The calibration certificate

Calibration Certificate

Calibration Company Ltd | Europe

Date of Test: 29th December 2022

Certificate No:	2345-678912	Due Date:	28th December 2023
Customer:	constructandcommission.com		
Address:	Construct and Commissioning House, Construct Way, Commissioning City, Construct County,		
Order Number:	PO-2374573		
Order Date:	21st December 2022	Date of Receipt:	27st December 2022

Item Tested

Description:	Electronic Balometer
Manufacturer:	ALNOR
Model Number:	PH731
Serial Number:	S123245467-09

Test Conditions

Temperature:	(23+/-3)°C
Humidity:	(50+/-25)%
Supply Voltage:	n/a

Test Specification

Type: **Calibration Check**

Document Procedure:

123-GFHBV-5642

Test Results

All results were within the manufacturers specification.

The Results are shown in the attached pages

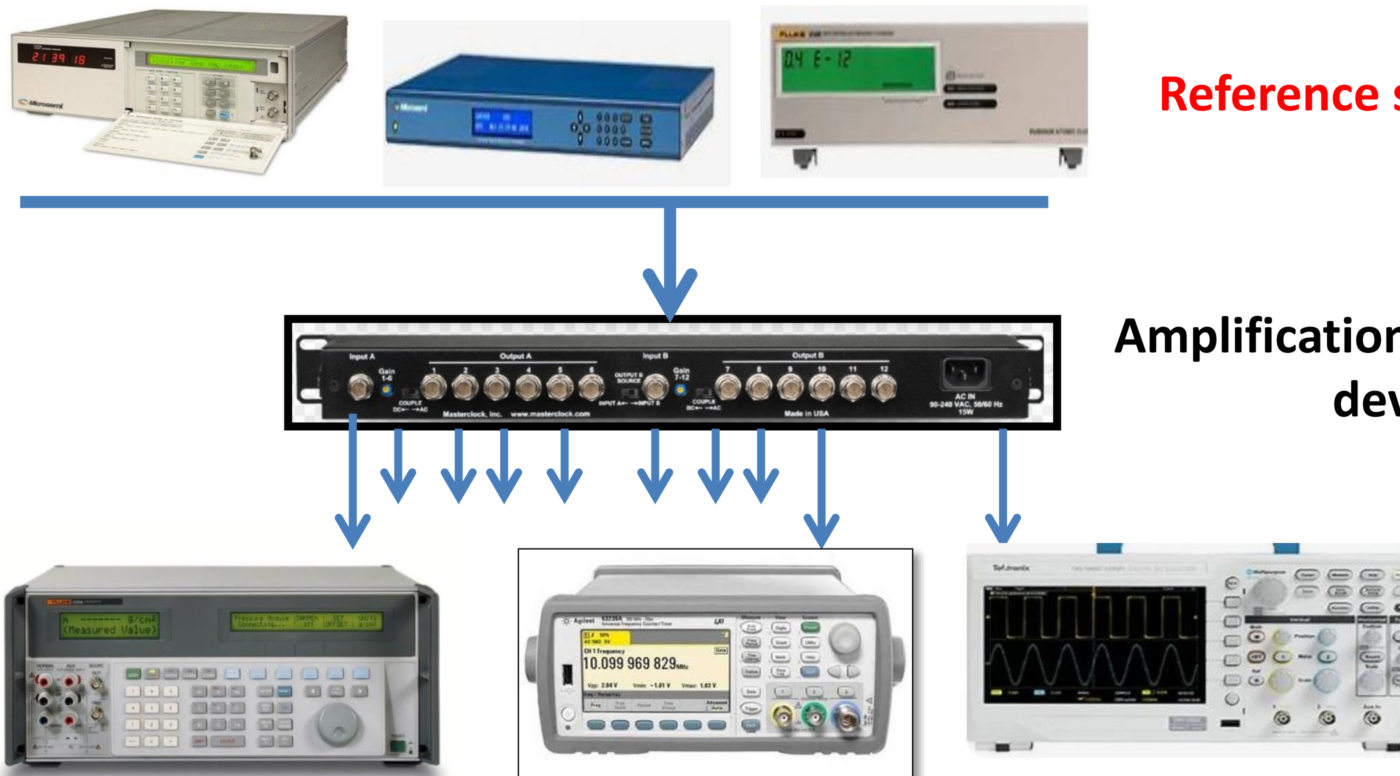
Test Equipment Used

Equipment No.	Description	Cert No.	Traceable to
S2435A	*Std. Thermometer*	*586415*	*NIST*

Calibrated By: *Bob Morris*

Approved By: *Mrs Morris*

Frequency Calibration
-Setting up-



Reference standard

Amplification/distribution device

Standard

Synthesizer

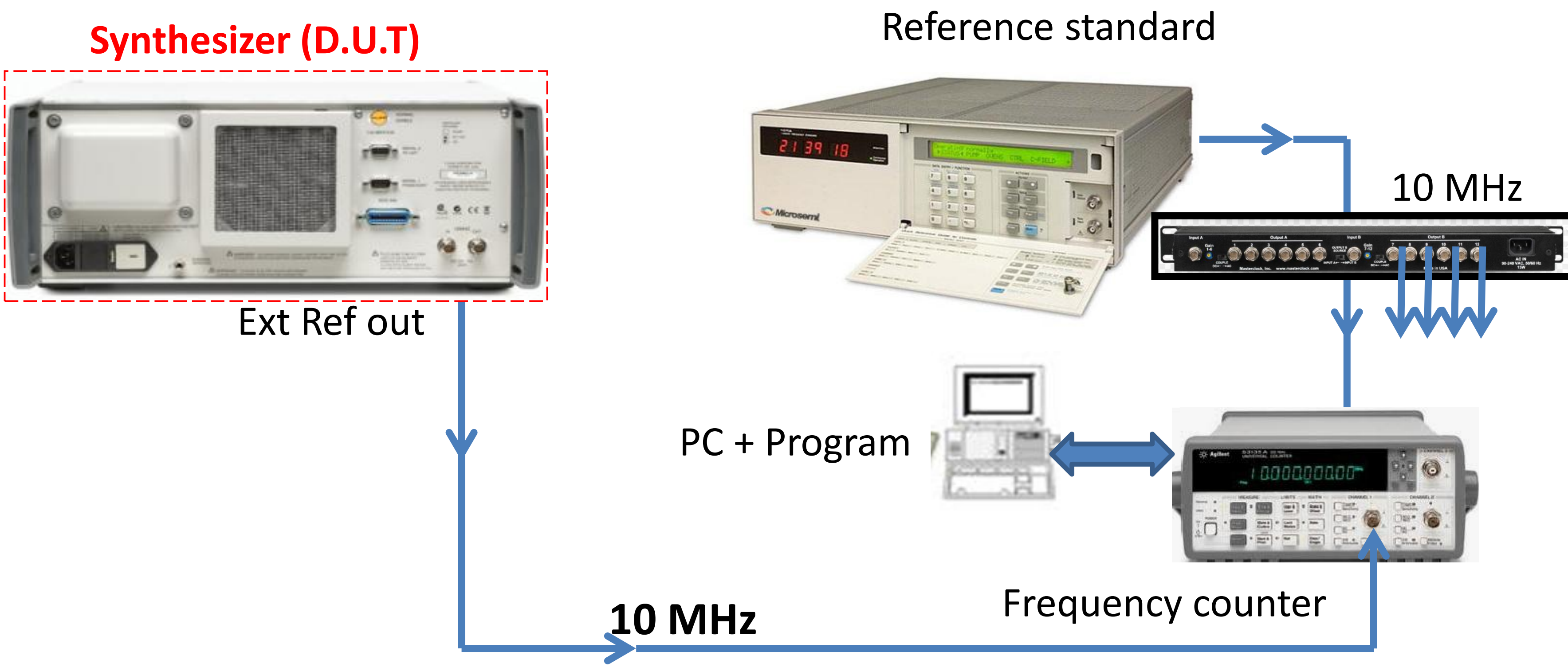
Frequency counter

Oscilloscope

Frequency Calibration

-Setting up-

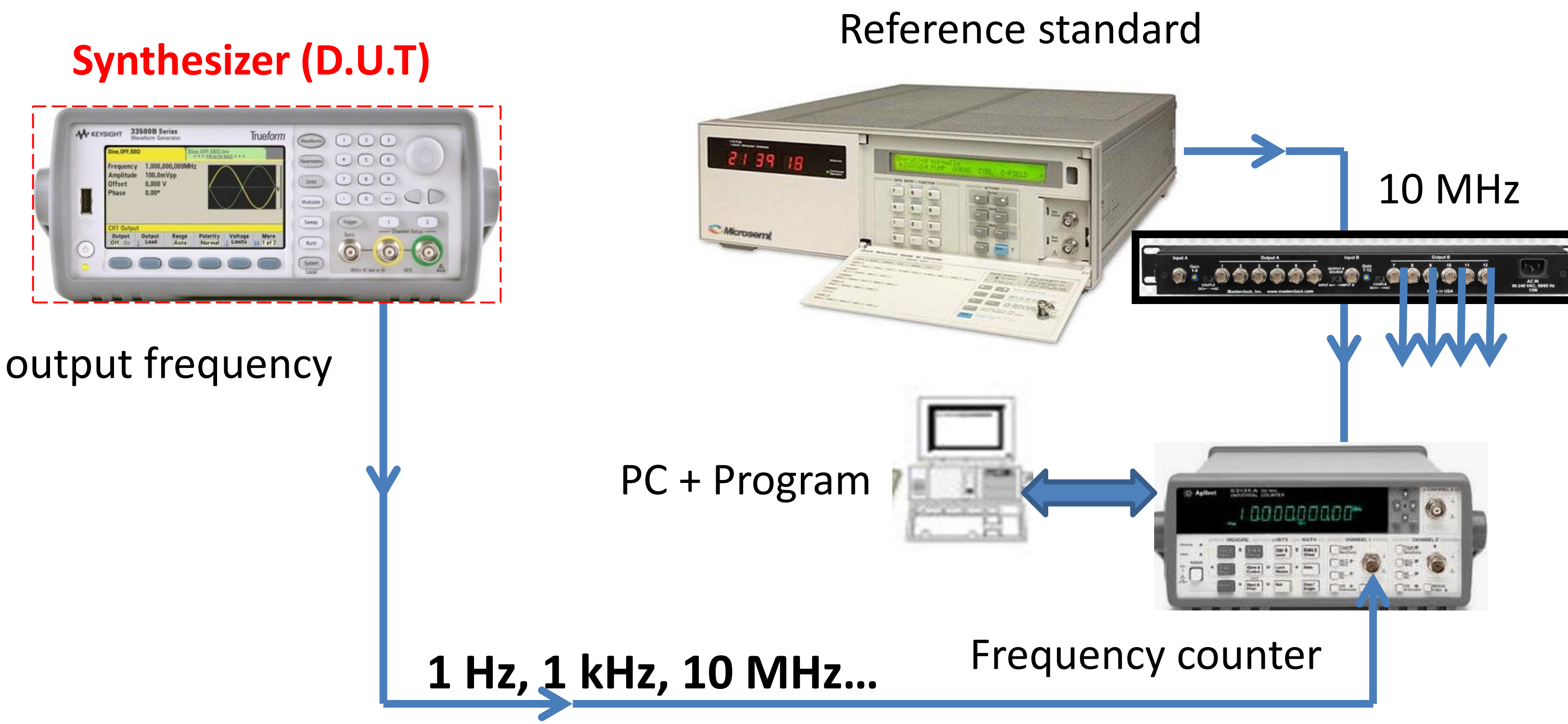
Synthesizer calibration (Rear panel)



Frequency Calibration

-Setting up-

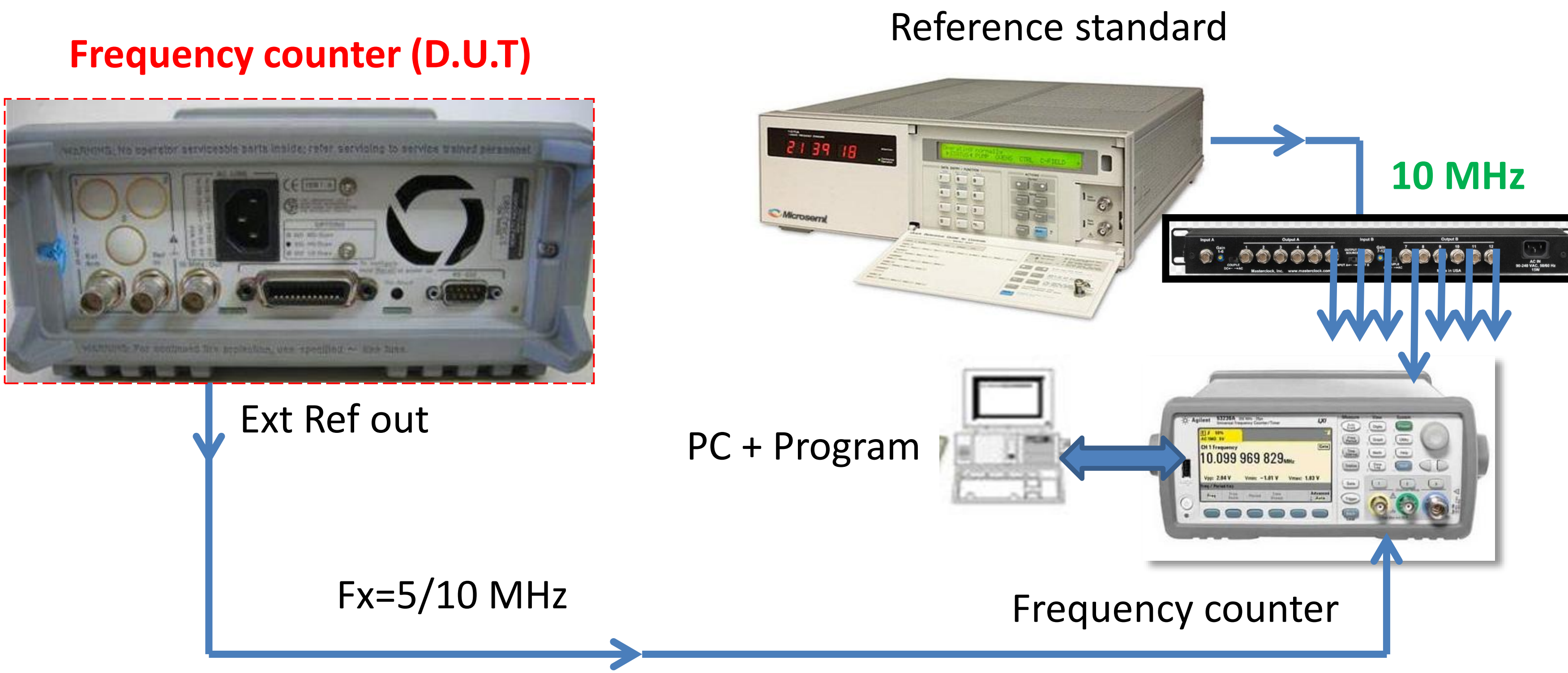
Synthesizer calibration (front panel)



Frequency Calibration

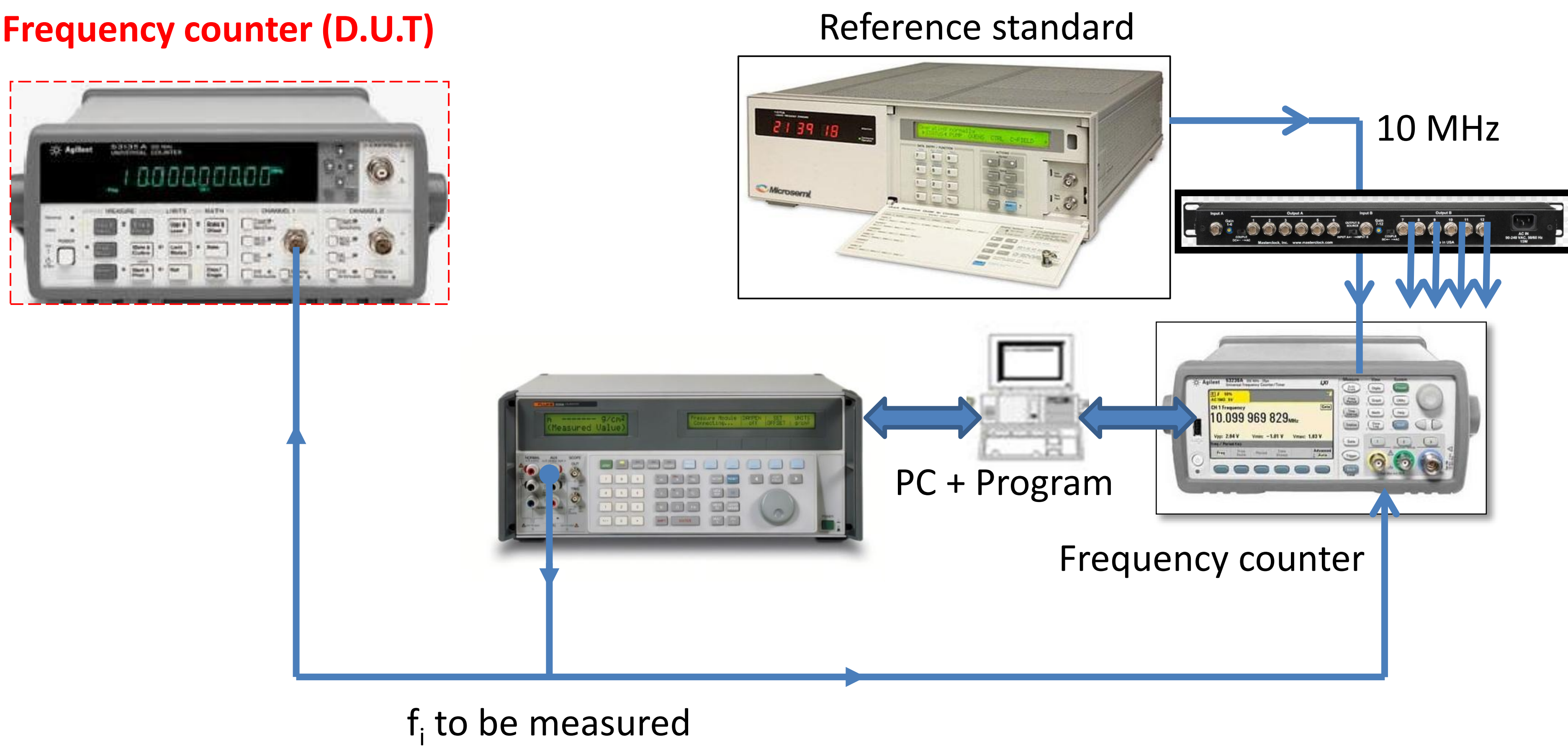
-Setting up-

Frequency counter calibration (rear panel)



Frequency Calibration
-Setting up-

Frequency counter calibration (front panel)



Frequency Calibration
-Configuration-

Equipments Setting

Synthesizer:

- Shape of signal: Square, Sine…
- Frequency to be measured
- Output Impedance: 50 Ω/1 MΩ

Frequency counter:

- Coupling: AC/DC
- Observation time (Gate time)
- Impedance 50/1MΩ
- Filter 100 kHz (LPF)
- Trigger level (V)
- Reference to be used: Yes/No (Internal/External)

Frequency Calibration -Calculation-

1- Quartz oscillator calibration

-Take N=10 samples (f_i) with your frequency counter (reference)

-Calculate the mean $f_m=\sum(fi)/N$

-Calculate the stability σ for τ=10 s

-Calculate the term of uncertainty due to the stability

σ/sqrt(N)

Frequency Calibration
-Calculation-

- **Average frequency (Hz)**

$$f_{measured} = f_{av} = (1/N)\sum fi \qquad (i:1 \rightarrow N)$$

- **Measurement error or Correction (C)**

$$Error = f_{reference} - f_{measured}$$

Uncertainty Budged

Typical uncertainty contributions

Type A uncertainties:

Often called Random uncertainty

A1: Repeatability of the measurement

A2: Stability of the frequency to be measured

Uncertainty Budged

Typical uncertainty contributions

Type B uncertainties:

All other uncertainties that cannot be determined statistically.

Type B is called Systematic uncertainty and it can be:

-Uncertainty due to the calibration of the reference

-Equipment performance specifications (given by manufacturer)

-Resolution (DUT)

-Drift, Aging…

Uncertainty Budged

Combining the uncertainty contributions

The final uncertainty is the calculation of the combined estimate of all individual Type A & Type B

$$U_c = k \times (U^2_1 + U^2_2 + U^2_3 + U^2_4 + \ldots. + U^2_n)^{1/2}$$

- U_c: expanded uncertainty
- k: coverage factor
- k=2 → 95% of confidence
- k vary from 1 to 3

Calibration report
-Recommendation-

You should indicate in the Calibration report important information according to the ISO 17025 (2017):

- Period of calibration
- Standards used for calibration
- Parameters of configuration : Output 1/2, Input1/2, impedance, filter (On/OFF), Coupling AC/DC, time of observation τ…
- Traceability of the reference
- Results: Nominal value, Error and associated uncertainty

Calibration report
-Example of report 1-

Nominal frequency (Hz)	Measurement error (Hz)	Calibration uncertainty (Hz)
1	-0,000 01	0,000 04
10	-0,000 1	0,000 1
100	-0,001	0,002
1 000	-0,01	0,03
10 000	-0,1	0,2
100 000	-1	1
1 000 000	-10	10

Calibration report
-Example of report 2-

Nominal frequency (Hz)	Averaged frequency Reference (Hz)	Averaged frequency (D.U.T) (Hz)	Calibration uncertainty (Hz)
1	1. 00000	1.00012	0.00010
10	10.00000	10.00124	0.00012
100	…	..	…
1 kHz	…		
10 kHz			
1 MHz			
1 GHz	1 000 000.01	1 000 000.45	…

المنظمة العربية للتنمية الصناعية والتقييس والتعدين

التجمع العربي للمترولوجيا

الوكالة الوطنية للمترولوجيا

المخبر الوطني للمترولوجيا

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