

Test and measurement for precise frequency sources meeting 5G holdover TIE 100...400 ns per 4...24 hours.

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1. Cellular networks synchronization

Synchronization is an essential prerequisite for all mobile networks to operate. It's fundamental to data integrity, and without it data will suffer errors and networks can suffer outages. Radio base stations rely on having access to reliable and accurate reference timing signals in order to generate radio signals and maintain frame alignment. Effective synchronization also permits hitless handover of subscriber connections between adjacent radio base stations

Historically frequency synchronization has been provided either by a Global Navigation Satellite System (GNSS) or derived from the transport network to which the network device requiring synchronization was connected. Public GNSS provides an accurate and stable synchronization source, but the financial cost to equip every site in a network with a GNSS-derived synchronization source may be prohibitive because of the requirement to install and manage additional equipment. Cost concerns for GNSS synchronization are more prevalent for small cell sites where the number of sites is increased compared with macro sites.

Telecommunication networks rely on the use of highly accurate primary reference clocks which are distributed network-wide using synchronization links and synchronization supply units.

Primary reference clock (PRC) or primary master clocks must meet the international standards requirement for long term frequency accuracy. To get this performance, atomic clocks or GPS disciplined oscillators are normally used.

Synchronization supply units (SSU) are used to ensure reliable synchronisation distribution. They have a number of key functions:

1. Filter the synchronisation signal they receive to remove the higher frequency phase noise,
2. Provide distribution by providing a scalable number of outputs to synchronise other local equipment,

3. Provide a capability to carry on producing a high quality output even when their input reference is lost, this is referred to as holdover mode.

2. 5G requirements

5G backhaul networks have higher requirements for frequency and time synchronization compared to all previous generations.

As mobile networks eventually migrate from LTE Advanced (LTE-A) to 5G, there are three fundamental changes that will have the most significant upstream impact on mobile backhaul networks:

- 10- to 15-fold increase in capacity (from LTE/LTE-A capacity of ~100Mbps to ~10 Gbps in 5G) .
- Ultra-low latency of ~1 ms (round trip).
- Ultra-dense nature of the network will also set unprecedented requirements for the synchronization of the cell sites as small and overlapping cell sites proliferate.

For 5G, higher accuracy time synchronization requirements are raised due to new services, technologies, and network architecture:

- New Services
 - High Accuracy Positioning service. High accuracy location capability: less than 3 m on 80 % of occasions in traffic roads and tunnels, underground car-parks, and indoor environments
- New Technologies
 - Carrier Aggregation. Carrier aggregation enables the use of multiple carriers in the same or different frequency bands, to increase mobile data throughput.
 - Coordinated Multi-Point Technologies
 - 5G Frame Structure
- New Network Architecture
 - Back-haul and Front-haul

Carrier Aggregation technologies require the time error between the base stations to be less than 260ns. 5G new frame structure under study may require as high as +/-390ns accuracy for the air interface to avoid interference. The 5G network would combine C-RAN and D-RAN. The time synchronization should be achieved in both the back-haul and front-haul transport network. [2]

Time interval error (TIE) is the metric to specify clock accuracy/stability requirements in telecommunication standards. Of specific interest is the TIE of a network clock in holdover mode (not locked) for mobile networks.

The key requirement for 5G communication networks is a TIE of 400...100 ns in holdover mode[1].

Frequency stability vs. temperature and long-term stability (aging) are the key parameters of precision frequency sources which have the maximal influence on TIE in holdover mode.

This article covers measurements and some results obtained for precision frequency sources ensuring TIE of 100 ... 400 ns for 4 ... 24 hours.

3. Measurement procedure.

TIE measurements are done for 3...7 days with periodic temperature changes. Measurement duration of 3...7 days is necessary to count and compensate frequency drift due to aging.

In general, it may be possible to compensate aging in holdover mode in case there is a long-term record of frequency output of precise frequency source obtained while it was synchronized to external reference. It is possible to create learning systems capable of aging compensation basing on data from the last 2...3 days of operation.

TIE estimation, which takes into account the compensation of the aging, is carried out as follows (Fig.1):

1. Choosing the beginning of TIE estimation (beginning for the “sliding” time window).

The «sliding» time window, moving with some step (1...4 hours), is applied to the data. This window consists of two parts: *Fit range* and *TIE estimate range*.

2. Approximation for the aging.

Frequency aging approximation $\varphi(t)$ is being built basing on readings situated inside *Fit range*. Lasting of *Fit range* – 24 hours. According to our researches, this is most optimal lasting for line aging approximation.

3. TIE estimation

Readings situated inside of *TIE estimate range* are being used for determination of subject time error. The time error in this range will be determined by the difference

between frequency readings and aging approximation: $TIE = \int [f(t) - \varphi(t)] dt$.
 Lasting of *TIE estimate range* – 4...24 hours.

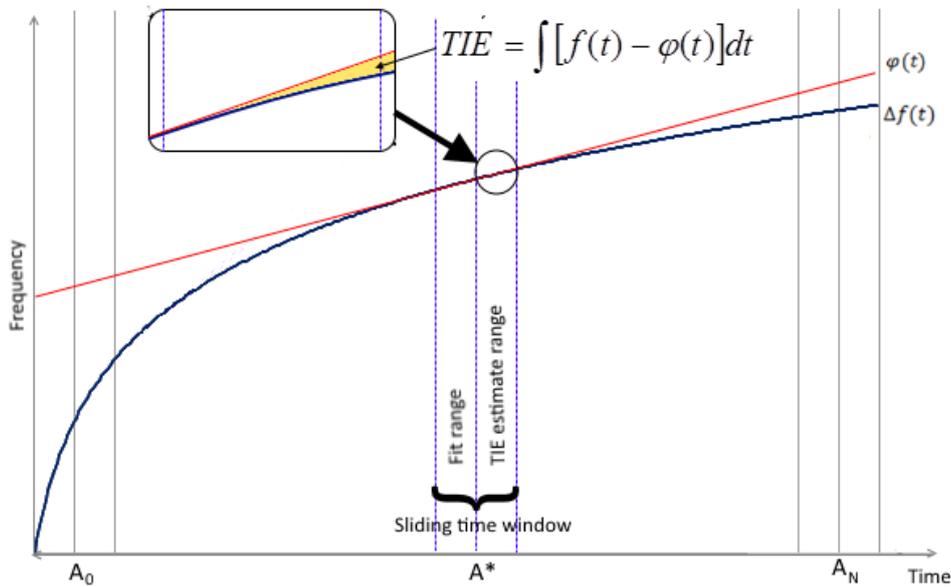
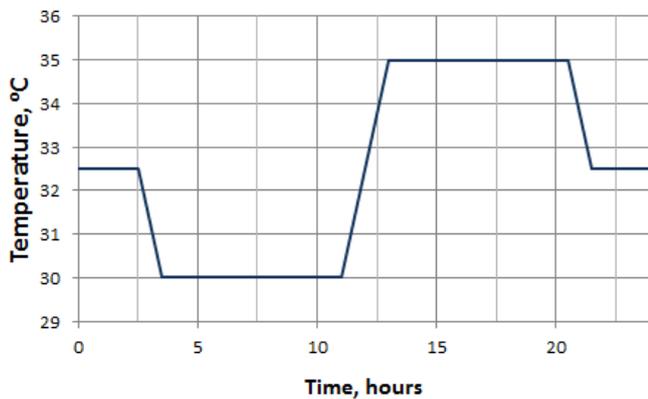


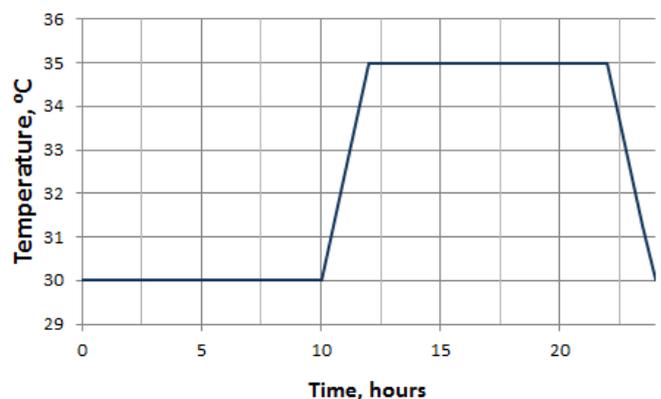
Fig.1 TIE estimation algorithm.

TIE of 400...100 ns in holdover mode for telecom and mobile networks is used primarily for grand masters, which are installed in an environmentally conditioned room. This means that the temperature change during the day usually does not exceed 5 °C.

Different temperature profiles can be used for TIE estimation. Two profiles for TIE estimation are presented in Fig.2. It should be mentioned that profile at Fig.2a is symmetrical due to the average temperature change. Thus, the time error accumulated over 24 hours along this profile should be equal to 0 (under ideal conditions). The profile shown in Fig.2b does not have symmetry, so even under ideal conditions there will be a time error accumulated within 24 hours.



a



b

Fig.2 Temperature profile for TIE estimation.

For TIE estimation we are using temperature profile from Fig.2b because it models the worst case of operation for precise frequency source.

An example of TIE estimation for DOCXO by the measurement procedure mentioned above can be seen in Fig.3:

Fig 3-A – temperature profile during test

Fig 3-B – obtained frequency readings (dashed shows “sliding” time window position)

Fig 3-C – TIE estimation result (TIE vs sliding time window position)

TIE estimation result obtained by procedure mentioned above:

1. For initial “sliding” window position (A) calculated approximation line, based on frequency counts situated on fit range.
2. Data inside of *TIE estimate range* used for determination time error.

$$TIE_A = \int [f(t) - \varphi(t)] dt.$$

3. Calculated TIE_A value located at Fig 3-C
4. Sliding time window make steps by 1 hour and all calculations repeated
5. This procedure continues until *TIE estimate range* will not go beyond measurements length.

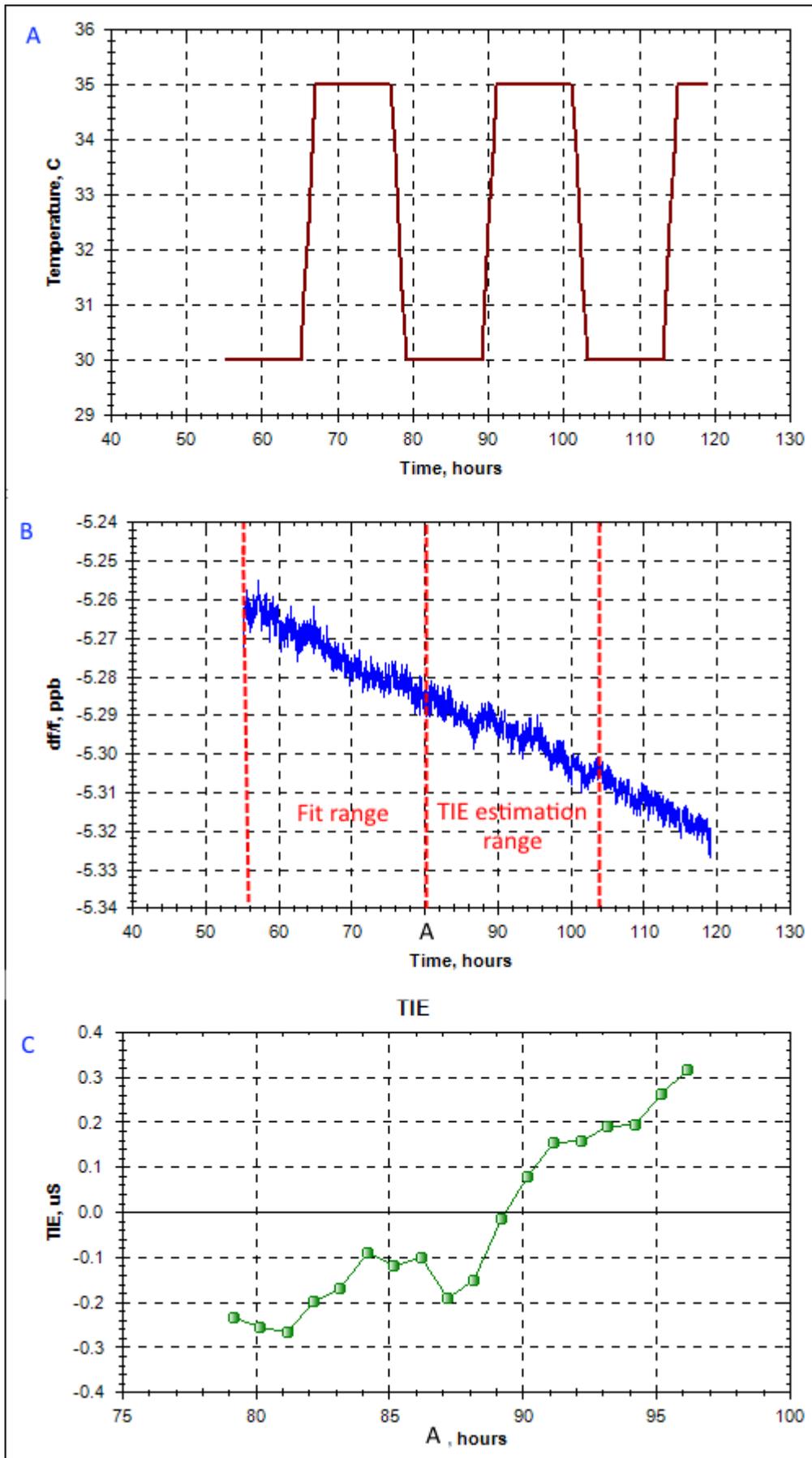


Fig.3 24 hour TIE for DOCXO

4. Features of TIE measurements.

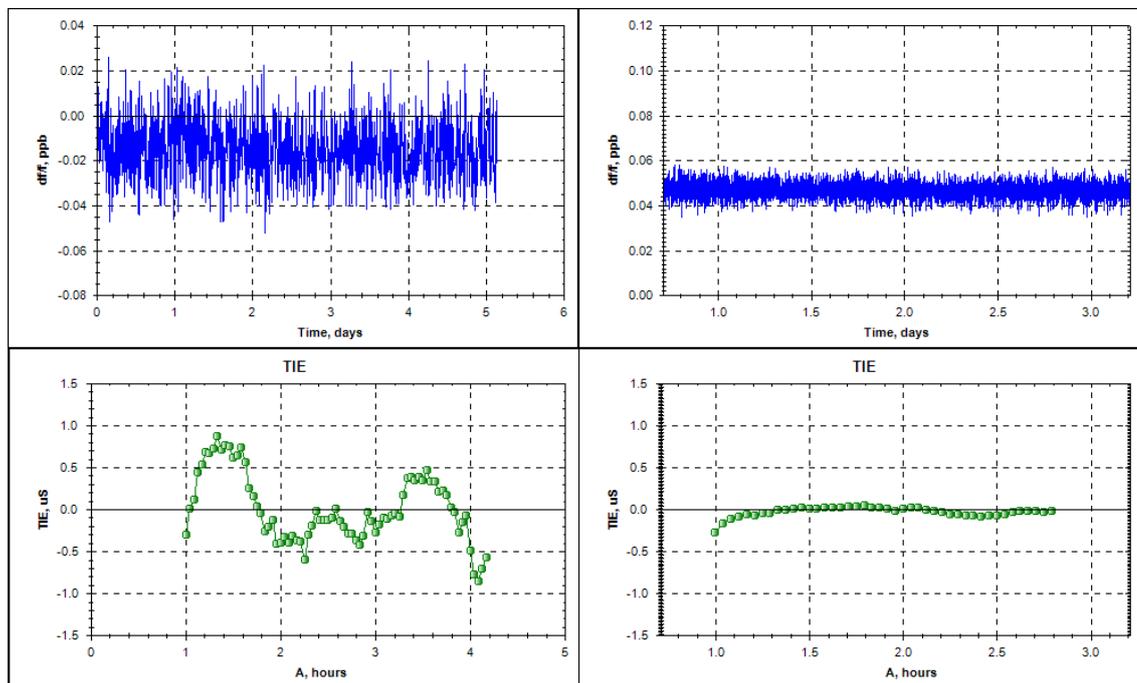
Even negligible frequency changes influences TIE estimation results. Sources of errors should be taken into account in order to obtain reliable values of TIE:

1. Mutual syntonization of the frequency of individual oscillators.
2. Frequency measurement instability.

4.1. Mutual syntonization of frequency

Mutual syntonization of frequency for oscillators which are oscillating at close frequencies is one of the most important sources of errors for frequency measurement. This effect may be easily seen in volume production, when simultaneously a large number of oscillators are measured. To prevent this effect, it is necessary to minimize all possible ways of influence of oscillators on each other: on the common grounds of power circuits and circuits of frequency switchers, through electromagnetic connection, reverse signal transmission through the open channels of the switcher.

As an example, one can see results of rubidium oscillators TIE measurement before and after the implementation of the above measures on Fig.4.



a

b

Fig.4 Measurement of frequency and TIE estimation for rubidium oscillator a) before and b) after implementation of the above measures to prevent mutual syntonization of frequency.

4.2. Frequency measurement instability.

For precision frequency sources to meet TIE 100...400 ns it is extremely important to have aging curve monotonicity of about $1...2E-11/day$. In other words, they should have no jumps or any other irregular frequency changes.

On Fig.5 you can see aging curve satisfactory to meet the TIE 100...400 ns requirements (Fig.5a). At the same time “standard” aging curve on Fig. 5b clearly shows "short-term" frequency changes, resulting that this oscillator will not meet the TIE requirement of 100 ... 400 ns.

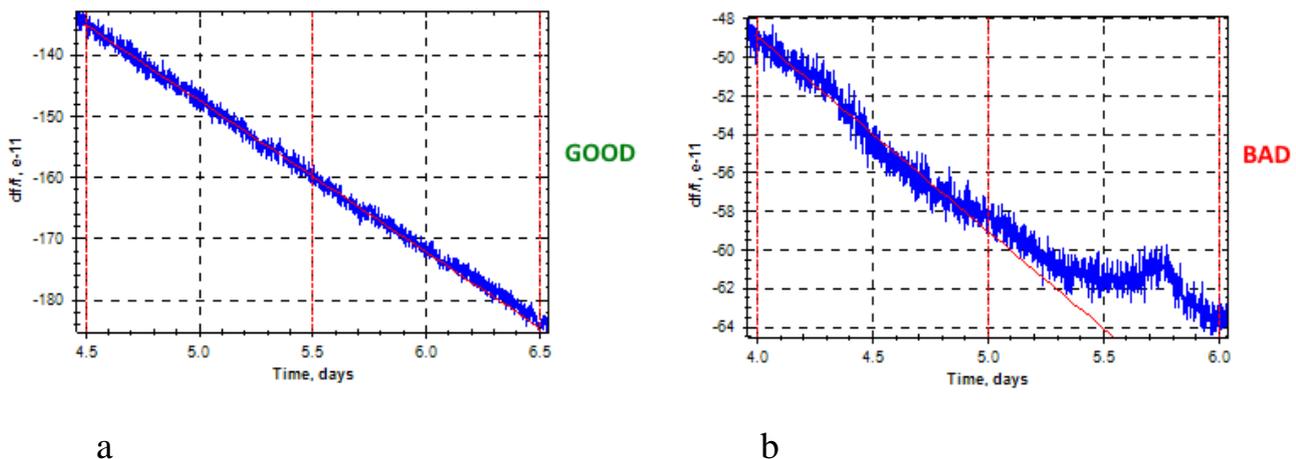
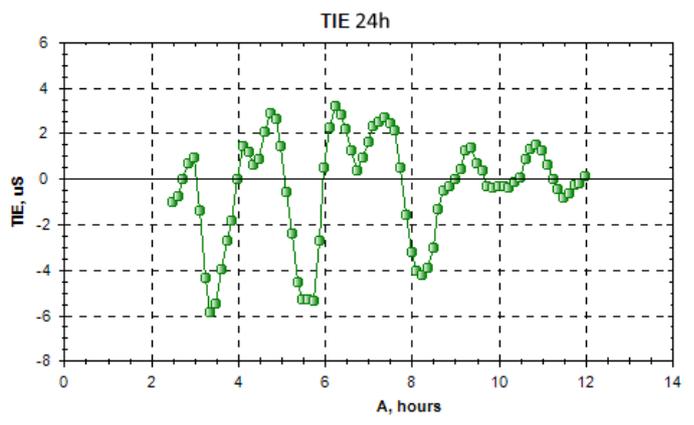
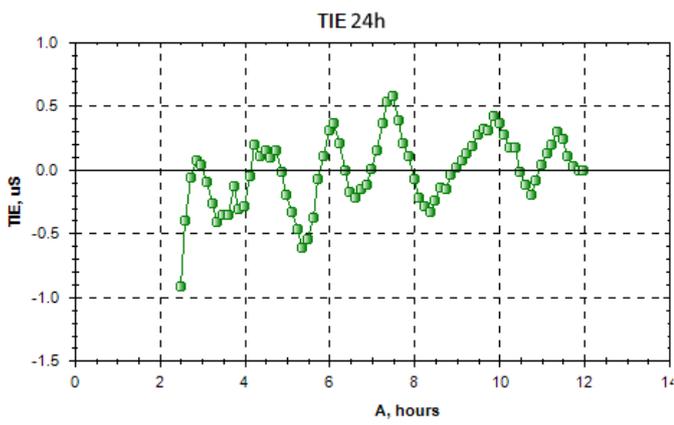
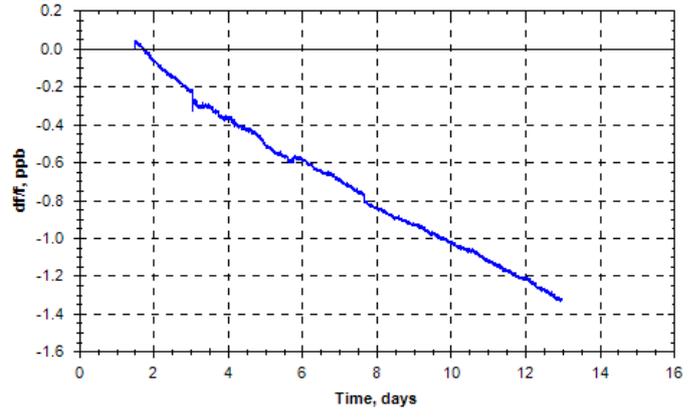
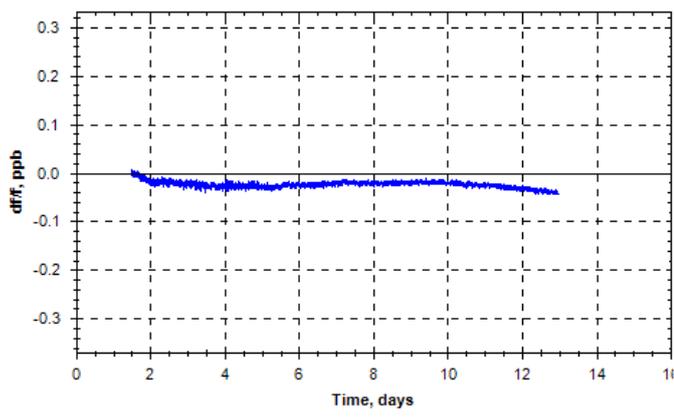


Fig.5 Figure 5a aging curve satisfactory for TIE of 100...400 ns requirement. Figure 5b shows “standard” aging curve.

It should be taken into account that the reasons for “short-term” frequency changes may be explained by either contact phenomena, stability of the reference source or errors caused by internal issues in the precision frequency sources.

To separate internal issues inside the precision frequency sources from the other phenomena good quality connectors and precision reference sources should be used. During measurements it was revealed that some precision rubidium oscillators, regardless of the manufacturer, can dramatically change frequency in increments ranging from $5e-12$ to $5e-11$. Taking into account what was mentioned above, we are using the hydrogen frequency standard for 100 ... 400 ns TIE measurements.

The example of TIE measurement for quartz oscillator with and without “short-term” frequency changes presented at Fig. 6.



a

b

Fig.6 Frequency and TIE measurement for quartz oscillator a)without and b)with “short-term” frequency changes

5. Results

TIE measurements will be reliable if all factors listed above will be taken into account. Example of measurement of TIE per 4, 8, 16 and 24 hours you can see at Fig.7.

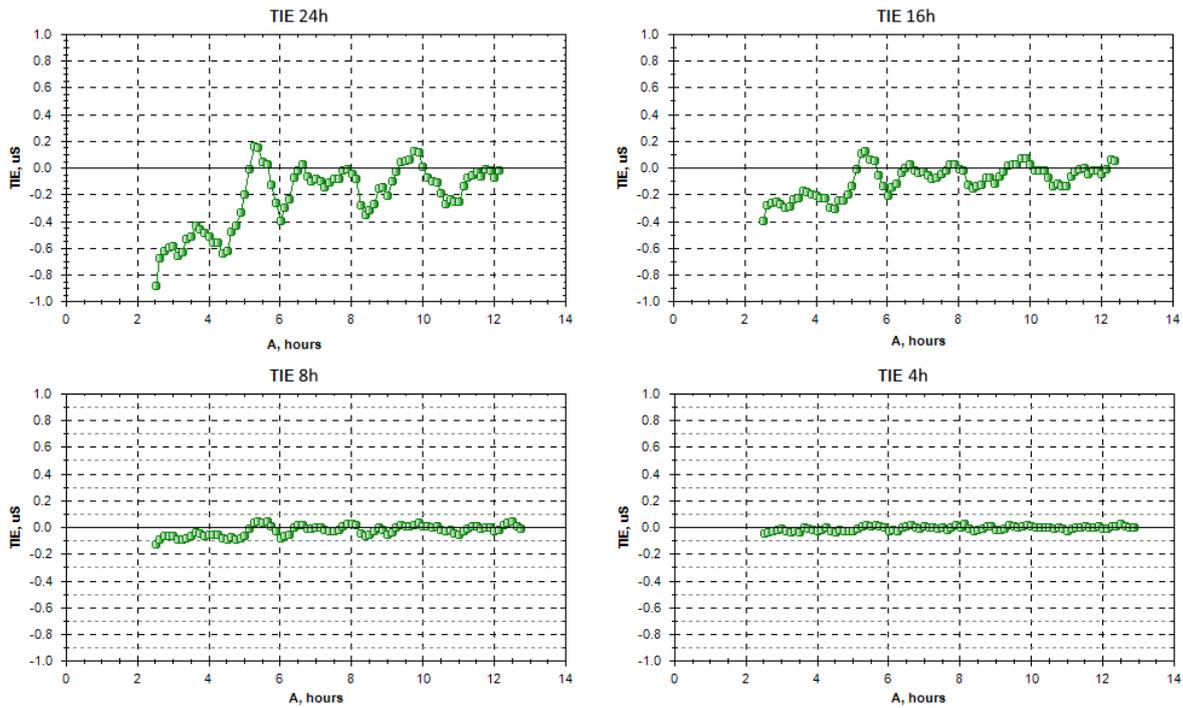
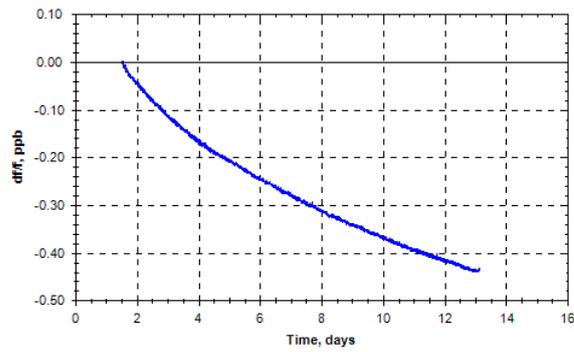


Fig. 7 Measurement of TIE per 4, 8, 16 and 24 hours

References

- [1] 3GPP TS 38.104 specification
- [2] Han Li, Liuyan Han, Ran Duan , Synchronization Requirements of 5G and Corresponding Solutions, IEEE Communications Standards Magazine (Volume: 1, Issue: 1, March 2017)