Final Report on EUROMET (EURAMET) Project No.847

„Metrology applications of dual-mixer time-difference multiplication„

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Introduction

The Project No. 847 was intended to be an expansion of the previous EUROMET Project No.651 "Ultra-sensitive short-term frequency and phase stability measurement" which was also coordinated from the Institute of Radio Engineering and Electronics (IREE), Czech Academy of Sciences (renamed as Institute of Photonics and Electronics -IPE- in 2008).

The Project No. 847 was inspired by the good results obtained within Project No.651 with the IPE's system for short-term frequency-stability (STFS) measurement based on dual-mixer time-difference multiplication (DMTDM). The IPE's measurement system designated as IPE2 showed very low background Allan deviation of about 7×10^{-15} at 1 s in 15 Hz bandwidth which was the best result ever achieved. Thus, naturally, the main goal of the expanded project was to further develop its basic application, i.e. in STFS measurement. A strong impulse for further research was the challenge for IPE to test the best BVA oscillators produced by Oscilloquartz (OSA). This was possible thanks to collaboration with FEMTO-ST, Besançon, which officially joined the Project in 2006. FEMTO-ST also arranged the collaboration with OSA which resulted in a series of measurements of BVA oscillators at IPE.

The high sensitivity of the DMTDM method suggests itself for other metrology applications besides the STFS measurement. A possible use is an accurate measurement of small delays in elements such as connectors, adaptors and short cables introduced into one of the two DMTDM input branches. The work on this application was done primarily in collaboration with LNE-SYRTE, Paris.

Another application we thought to be worth of investigating was the use of DMTDM in measurement of physical quantities that could be transformed into time delays through appropriate probes introduced into the DMTDM input. In this case the measurement would concern instability of the quantity rather than its absolute value (this way e.g. vibrations could be measured).

The Project started June 1st, 2005 and was originally planned for two years only. As approved at the 2008 Annual Meeting of EURAMET Technical Committee for Time and Frequency held in Prague, the Project was prolonged till the end of 2008.

The aim of the proposed project was to facilitate cooperation in solving the following problems:

1) Application in frequency (phase, time) short-term stability measurement: determination of the practical limit of the noise floor by experimenting with a new version of the IPE DMTDM whose construction would be based on the experience gained from previous research.
2) Application in time-delay measurement: investigation of the performance of DMTDM in measurement of small delays in elements such as short cables, connectors and adaptors introduced into one of the DMTD input arms. A special version of the DMTD multiplier optimized for this application would be constructed.
3) Application in measurement of other physical quantities that can be transformed into time delay: The idea is to make use of the extreme sensitivity of DMTD multiplication for sensing variations in these quantities.

DMTDM measurement structure

The basic block diagram of DMTDM which has been investigated within the Project is shown in Figure 1. It should be noted that the DMTDM principle has been known since 1975 [1].

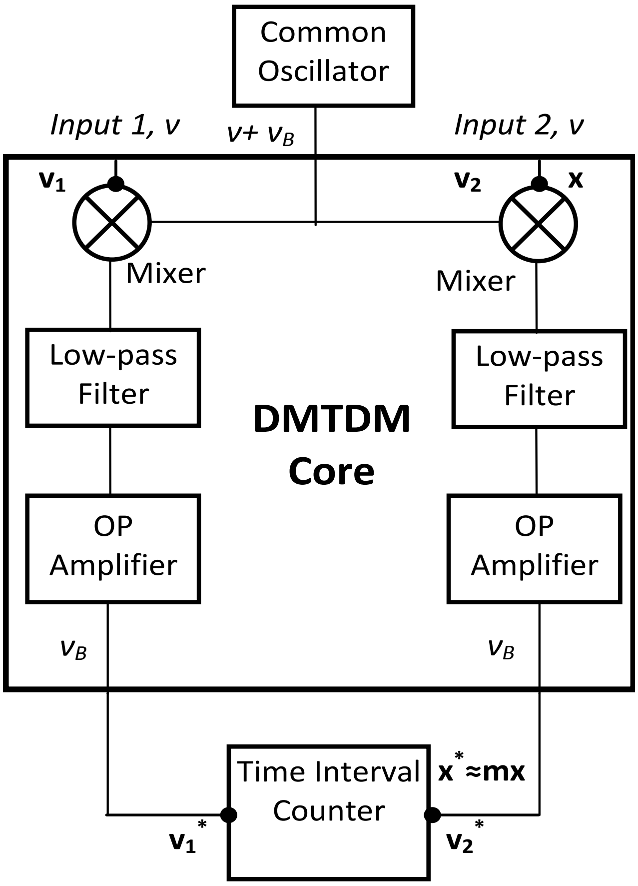

Figure 1 Basic DMTDM measurement structure.

The output time difference $x^*(t_k)$ can be described as

$$x^*(t_k) = m\left[x(t_k) + \varepsilon(t_k) + E(\nu, \rho_{R,j})\right] + \varepsilon^*(t_k) \tag{1}$$

where

$x(t_k)$	input time difference,
$m = \nu/\nu_B$	multiplication coefficient,
$\varepsilon(t_k)$	time dependent error before multiplication,
$E(\nu, \rho_{R,j})$	error due to reflections in configuration *R*,
$\varepsilon^*(t_k)$	error introduced after multiplication.

Three basic types of measurement

(1) Frequency stability

Input RF signals from two different sources:

$$E(\nu, \rho_{\mathrm{R,j}}) = \mathrm{const} \tag{2}$$

(2) Variations in time delay of an inserted element
Input RF signals from the same source:

$$E(\nu, \rho_{\mathrm{R,j}}) \approx \mathrm{const} \tag{3}$$

(3) Time delay of an inserted element
Input RF signals from the same source:

$$E(\nu, \rho_{\mathrm{R,j}}) \neq \mathrm{const} \tag{4}$$

Measurement of short-term frequency stability

A series of measurement campaigns at IPE on groups of OSA 8600/8607 BVA 5MHz oscillators (in collaboration with FEMTO-ST and OSA).

2006

Oscillators:

- S/N 102 (OSA)
- S/N 199 (FEMTO-ST)
- S/N 291 and S/N 315 (IPE)

Measurement Systems:

- IPE1 and IPE2 – laboratory DMTDM
- TSC 5110A – time interval analyzer

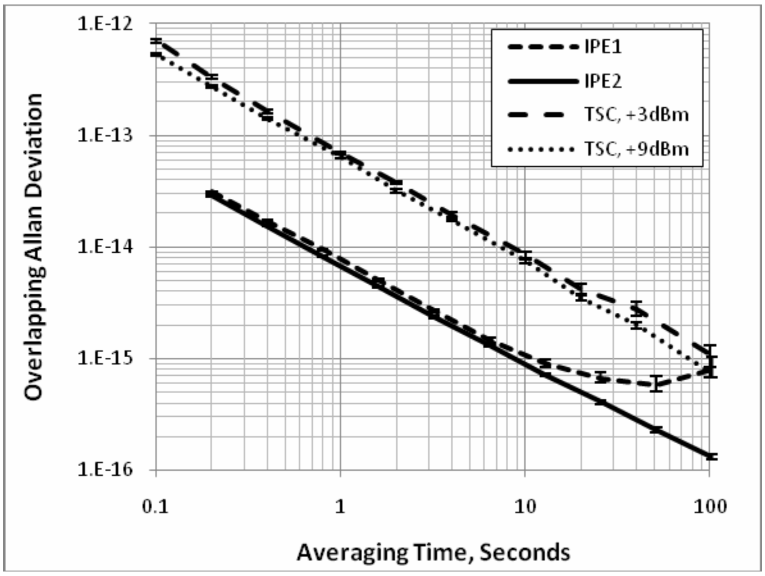

Figure 2. Background noise of IPE1, IPE2 and TSC tested by two signals from one BVA oscillator.

Observations:

- Irregular perturbations observed in some of the measurements (these came most likely from environment in spite of good conditions in the laboratory).
- False injection locks observed in some cases.
- A question arises about the interpretation of the results whether we should seek oscillator's "best capability" (which is of interest for the researcher or oscillator designer) or rather its "routine capability" (of interest for the user).

The results were published in [2].

2007

June

Oscillators:

- S/N 199 (FEMTO-ST)
- S/N 291 and S/N 315 (IPE)
- S/N 543 (OSA)

Measurement System:

- IPE2 – laboratory DMTDM

October

Oscillators:

- S/N 199 (FEMTO-ST)
- S/N 291 and S/N 315 (IPE)
- S/N 543 and S/N 567 (OSA)

Measurement System:

- IPE2 – laboratory DMTDM

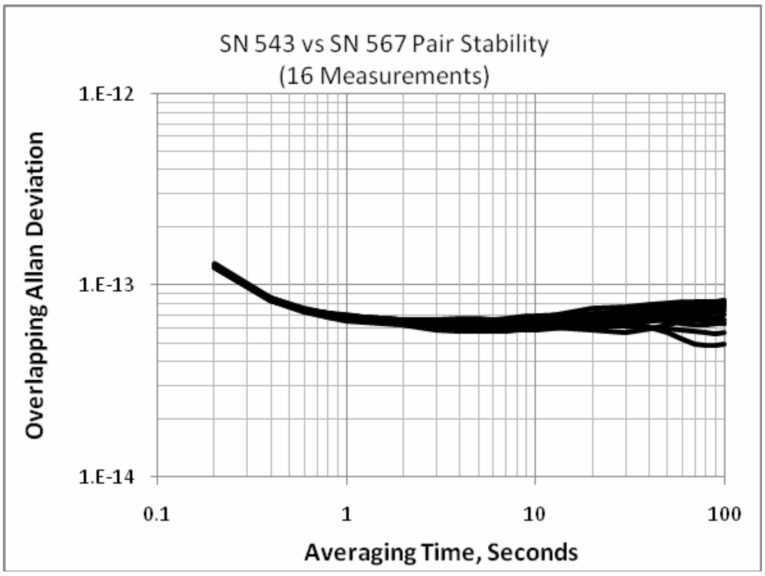

Figure 3. Best pair stability in the October campaign.

Observations:

- Good measurement reproducibility.
- No observable change in FFM.
- Difficulties with three-cornered hat decomposition.
- Excellent performance of S/N 543 and S/N 567 with the FFM floor of ~$4x10^{-14}$ assuming both oscillators with same performance.

2008

Oscillators:

- S/N 199 (FEMTO-ST)
- S/N 291 and S/N 315 (IPE)
- S/N 543, S/N 567, S/N 691 and S/N 692 (OSA)

Measurement System:

- IPE3 – laboratory DMTDM

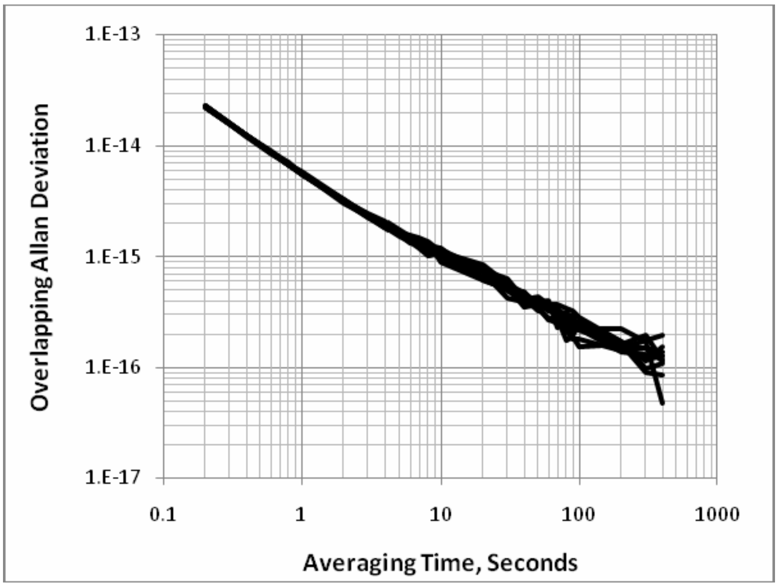

Figure 4. Background noise of IPE3 tested by two signals from one BVA oscillator.

Observations:

- Very good measurement reproducibility with no observable change in FFM.
- Background instability of IPE3 (5.5x10^{-15} at 1 s in 26 Hz bandwidth, see Figure 4) – best ever achieved.
- FFM floor of S/N 692 (~3.2x10^{-14} at 1 s in 26 Hz bandwidth, see Figure 5) – probably best ever measured on a BVA oscillator.

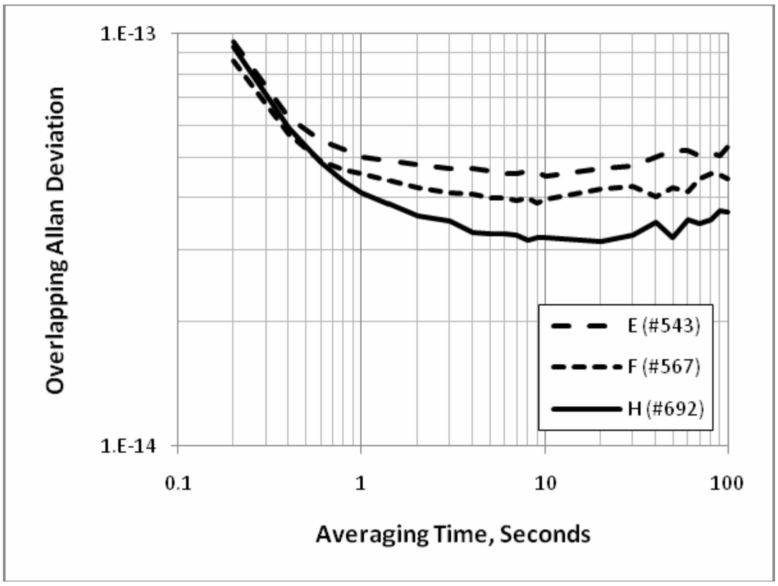

Figure 5. Decomposed frequency stabilities of the three best BVA oscillators.

Measurement of short delays

The principle has been described in [5] and experimental results in [6].

The test of repeatability shown in Figure 6 shows the method's uncertainty limits.

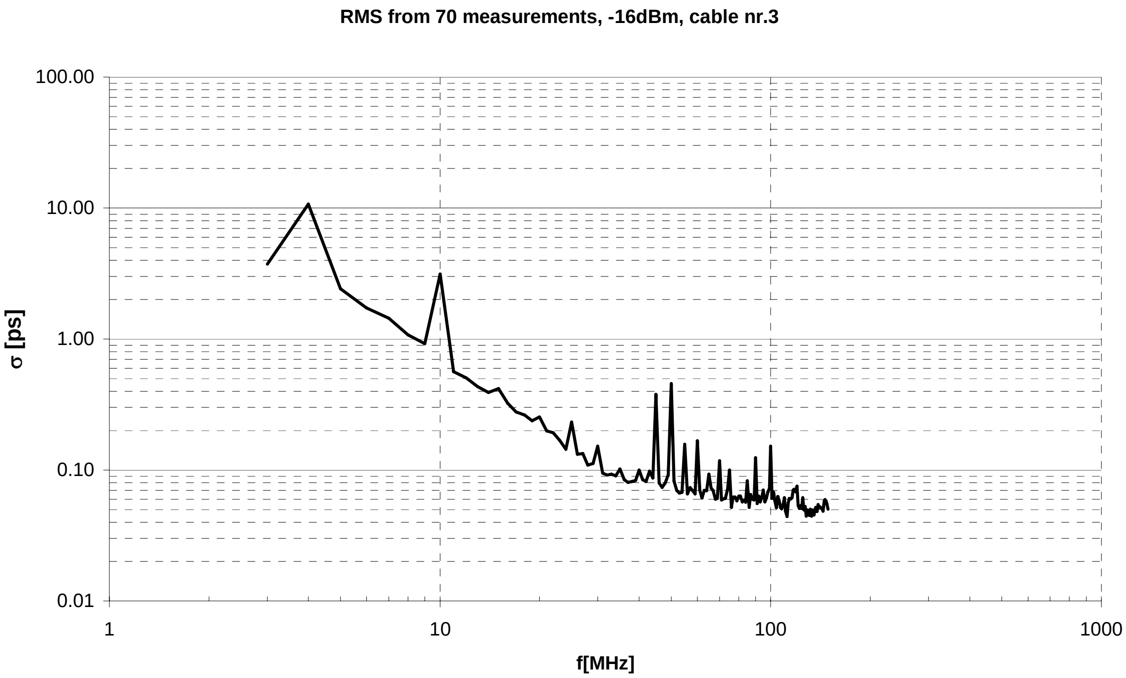

Figure 6. Repeatability in delay measurement.

Time error:

$$\varepsilon_{x} = \frac{T}{2\pi} arctg \frac{r \sin 2\pi \frac{x}{T}}{1 + r \cos 2\pi \frac{x}{T}} \quad (5)$$

where

T	RF signal period,
r	total reflection coefficient,
x	phase time between the incident and reflected waves.

For $r << 1, \quad \max(\varepsilon_{x}) \approx \pm \frac{rT}{2\pi}$.

Conclusions

Measurement of short-term frequency stability

- The IPE3 DMTDM measurement system's noise floor is the best ever reported. Thus IPE3 may serve as a reference for the future digital systems.
- The best OSA 8607 BVA oscillators show so an extremely low FFM which currently cannot be measured by industrial systems.

Measurement of short delays

A target uncertainty of ~1 ps uncertainty can be achieved. The fact is, however, that an accurate measurement of unstable delays such as in flexible cables or BNC connections has a limited use. The absolute measurement should concern only objects where the accuracy of 1 ps makes sense, such as SMA or PC 3.5 connections.

The problems to be solved are:

- Devising a physically justifiable frequency-dependent parametric model of the reflection error.
- Elaborating an unambiguous fitting algorithm. Otherwise the fitting algorithm may converge to a false extreme (i.e. to a false parameter set) and consequently to incorrect error $E(\nu, p_{R,j})$.
- Construction of a delay standard.
- Interconnection of the inserted (measured) element.

Measurement of other physical quantities

Given the limited research capacity within the Project and the need of investigating preferably the STFS measurement, this goal has not been achieved. Thus it has remained only as an idea for future research.

References

[1] D. W. Allan and H. Daams: "Picosecond time difference measurement system", Proc. 29th Annual Symp. Freq. Contr., Atlantic City, NJ, USA (1975), pp 404-411

[2] J. Čermák, A. Kuna, L. Šojdr, P. Salzenstein, Short-Term Frequency Stability Measurement of BVA Oscillators. Proc. Joint 2007 European Frequency and Time Forum and 2007 IEEE Frequency Control Symposium, Geneva, pp. 1255-1260 (2007).

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[4] Kuna, J. Čermák, L. Šojdr, P. Salzenstein, F. Lefebvre, Lowest flicker-frequency floor measured on BVA oscillators. Proc. 2009 European Frequency and Time Forum, Besançon, France, (2009)

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[6] R. Barillet, J. Čermák, L. Šojdr, A. Kuna, On twofold use of dual-mixer time-difference multiplication. 19th European Frequency and Time Forum, Besançon, France, March 2005, pp. 366-371