TIME TRANSFER IN OPTICAL NETWORK

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Abstract

This paper describes experiments with two-way time transfer in an optical network. The method is based on newly developed adapters utilizing channels in a DWDM (Dense Wavelength-Division Multiplexing) network. We present results of several tests performed in real production all-optical network including the time transfer between atomic clocks in Prague and Vienna over more than 500-km-long optical path. The method is assessed and compared with One-in-view GPS satellite at geographical distance about 100 km.

INTRODUCTION

Accurate time transfer between two geographically distant sites is dominated by satellite systems, either GNSS (Global Navigation Satellite Systems) or TWSTFT (Two-Way Satellite Time and Frequency Transfer). Communication networks provide alternative infrastructure for accurate time and frequency transfer. Large all-optical networks (i.e. networks without optical to electrical signal conversion) are built in the last few years. The background DWDM (Dense Wavelength-Division Multiplexing) technology offers a lot of so-called "lambda channels" that are also suitable for time and frequency transfer.

In recent years, stable frequency transfer in optical links has been studied [1,2], and several methods of long-distance time transfer were also developed. For instance, [3] and [4] design utilization of SDH asynchronous telecommunication links and [5] describes a novel method of one-way time transfer. This paper extends our previous experience [6] with two-way time transfer using DWDM channel.

SYSTEM ARCHITECTURE

Our time transfer system is an instance of a two-way transfer method that relies on symmetrical transport delay in both directions. Figure 1 shows the method and adapter interfaces. Two adapters are connected by a bidirectional optical link. Each adapter is provided by a 1PPS signal from a local clock and each adapter has two outputs: T_{Ri} (i = A, B) is a 1PPS signal received via an optical interface from the other adapter and T_{Si} represents the epoch the encoded 1PPS signal was sent out. Both T_{Si} and T_{Ri} signals are connected to STOP inputs of two time-interval counters (TIC). The first TIC measures interval x_i between T_i and T_{Ri} (i.e. the difference between local and remote 1PPS) and the second TIC measures the adapter delay ε_{Si}, i.e. the time between T_i and T_{Si} signals.

The 1PPS pulse from the local clock arrives to adapter **A** in time t_A. It is transmitted by adapter **A** through the optical fiber to the remote site in time t_{SA} and the reception is signalized by adapter **B** in time t_{RB}. Analogously, the 1PPS pulse from the remote clock raised in time t_B is transmitted by adapter **B** in time t_{SB} and received by adapter **A** in time t_{RA}. Thus, $\Theta_{AB} = t_B - t_A$ is the clock offset, $\varepsilon_{Si} = t_{Si} - t_i$; i = A, B is the delay of adapter i and $\delta_{AB} = t_{RB} - t_{SA}$ and $\delta_{BA} = t_{RA} - t_{SB}$ is the link delay from site **A** to site **B** and from site **B** to site **A** respectively.
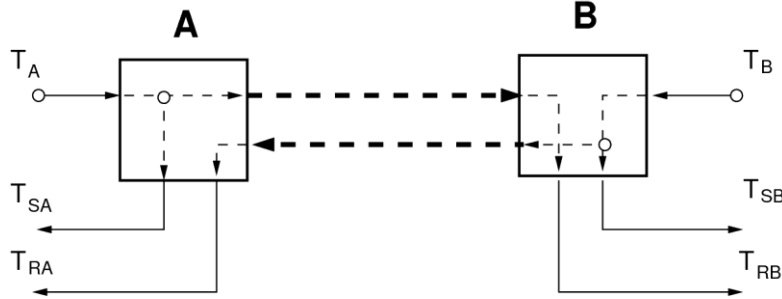

Figure 1. Method of time transfer.

METHOD OF MEASUREMENT

Using a pair of time-interval counters at both sites, it is possible to measure the adapter delays ε_{Si} and the time intervals

$$x_A = t_{RA} - t_A = \quad \Theta_{AB} + \varepsilon_{SB} + \delta_{BA}, \tag{1}$$
$$x_B = t_{RB} - t_B = -\Theta_{AB} + \varepsilon_{SA} + \delta_{AB}. \tag{2}$$

On a symmetrical link, the delay in both directions equals $\delta = \delta_{AB} = \delta_{BA}$. In a real network, the fiber length in both directions slightly differs (e.g., due to patch cords in the switching board, fiber compensating the chromatic dispersion), introducing a delay asymmetry Δ:

$$\Delta = \delta_{BA} - \delta_{AB}. \tag{3}$$

The clock offset Θ_{AB} may be then calculated as

$$\Theta_{AB} = ((x_A - x_B) + (\varepsilon_{SA} - \varepsilon_{SB}) - \Delta) / 2. \tag{4}$$

Knowing the clock offset Θ_{REF}, the link asymmetry Δ can be evaluated from

$$\Delta = (x_A - x_B) + (\varepsilon_{SA} - \varepsilon_{SB}) - 2\,\Theta_{REF}. \tag{5}$$

ADAPTER DESCRIPTION

Figure 2 displays the adapter structure. It consists of two main components: the FPGA chip Virtex 5 and the SFP (Small Form-factor Pluggable) transceiver. The optical signal arrives at the receiver part of the SFP, where it is converted into an electrical signal. The demodulator in the FPGA regenerates the carrier frequency and demodulates the 1PPS, which is as T_R connected to the STOP input of the TIC measuring the value x. The transmitter part contains the oscillator generating the carrier frequency – 250 MHz in current prototype. The oscillator can be either locked to an external 10 MHz reference or can be free running. The carrier frequency is then modulated by the 1PPS signal from the local clock. A delay up to 4 ns corresponding to the phase difference between the 1PPS signal and the carrier is introduced in the modulator. The modulator output T_S is connected to the STOP input of the second TIC measuring the parameter ε.
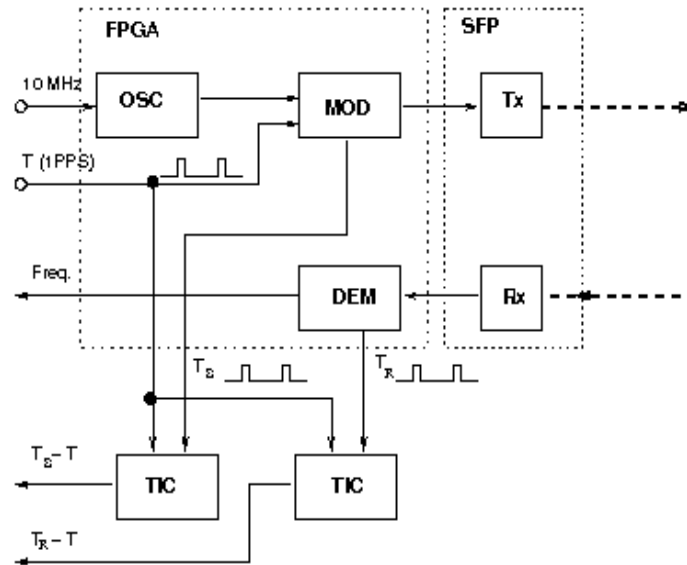

Figure 2. Adapter structure.

OPTICAL NETWORK

All our experiments were performed using two unidirectional "lambda" (dedicated wavelength) channels in the Cesnet2 network and the Prague metropolitan network PASNET. The Cesnet2 network is the Czech NREN (National Research and Educational Network) operated by the association CESNET. Figure 3 shows the DWDM backbone of the Cesnet2 network, including a ring providing two independent routes between the two main points of presence: Prague and Brno. The ring, which we used

in one of experiments, is 744 km long (plus another about 80 km of DCF – Dispersion Compensation Fiber) and is equipped with 12 Erbium-doped fiber amplifiers (EDFA). The 220-km-long cross-border fiber link between Brno and Vienna is equipped with optical booster and preamplifier.
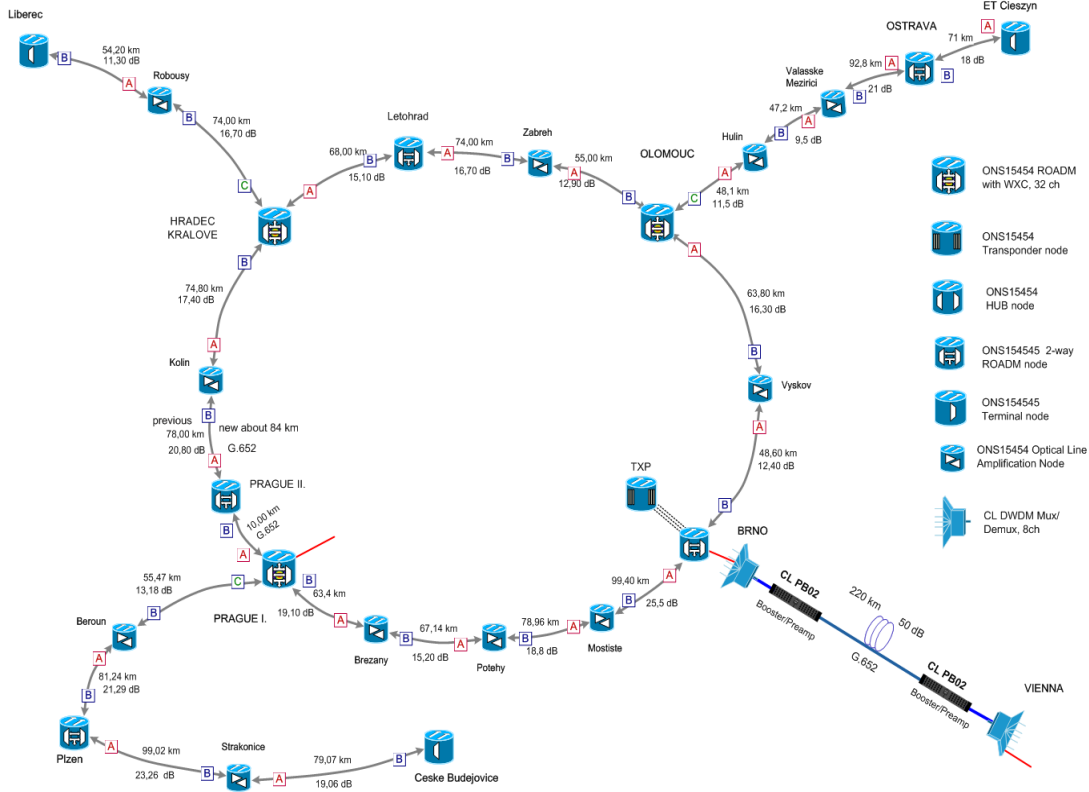

Figure 3. Cesnet2 network skeleton.

EXPERIMENTS

We performed set of experiments in order to verify the time transfer method, to test developed adapters and to evaluate accuracy in a real all-optical network. Experiments included measurements using an optical loop, demonstration of long-distance time transfer between Prague and Vienna, and comparison with Common View GPS transfer.

EXPERIMENT 1 – MEASUREMENTS ON AN OPTICAL LOOP

The goal of this experiment was to measure the delay of a long optical path in order to predict the influence of the fiber thermal dilatation on changes of the asymmetry Δ defined in (3). The 1PPS from a rubidium clock was transmitted in both directions and using two time-interval counters, the delays δ_{AB} and δ_{BA} were measured. We utilized a 744-km-long bidirectional optical loop – the route between the cities Prague – Brno – Olomouc – Hradec Kralove – Prague, as is shown in Figure 3.

Figure 4 displays the stability of the time transfer in terms of Time deviation denoted as TDEV or $\sigma_x(\tau)$ – we see that for averaging intervals up to 200 s, the white phase modulation $\sigma_x(\tau) \approx 100$ ps/$\sqrt{\tau}$ prevails. We

assume this noise originates apparently in the modulation/demodulation of the carrier signal and in the output circuits of the adapters. The lowest value of ~8.1 ps for an averaging time of 500 s has been observed. We described details of this experiment in **[1]**.
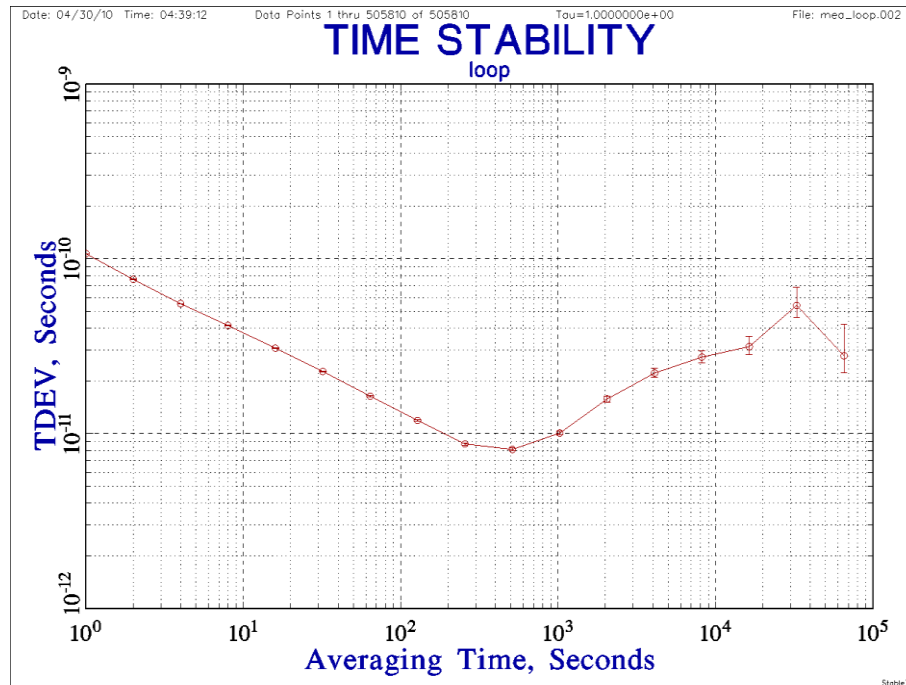

Figure 4. Time stability of optical loop.

EXPERIMENT 2 – TIME TRANSFER BETWEEN PRAGUE AND VIENNA

In addition to the national optical network infrastructure, CESNET operates also a cross-border DWDM fiber link from Brno to Vienna, where it ends on the premises of ACOnet (Austrian national research and education network) located on the Vienna University campus. The length of the optical fiber path between Prague and Vienna is 504 km, excluding the fiber compensating chromatic dispersion.

The experiment was aimed at time transfer between Prague and Vienna. In Prague, we used a GPS-disciplined rubidium clock PRS-10 (Stanford Research Systems). In Vienna, the situation was complicated by a not yet operational fiber link between Vienna University and the BEV premises. Therefore, BEV transported their rubidium clock (Quartzlock LPRO) to ACOnet, where it was operated as a free-running clock.

The measured time offset between the clocks is shown in Figure 5. As the clock in Prague was disciplined by GPS, we can conclude that the free-running rubidium clock in Vienna had a relative frequency offset of ~8×10^{-12}.

An interesting event is the discontinuity at MJD 55257-42569 which was caused by the unexpected replacement of an optical amplifier by another type with a slightly different length of dispersion compensating fiber (DCF). In the direction from Vienna to Prague, the one-way delay was increased by 72 ns (i.e. the new DCF is about 14 m longer); in the opposite direction, the increase was 16 ns (about

431

3 m). This incident demonstrates the vulnerability of time transfer utilizing two fibers; however, in the case of continuous measurement, such an event can be identified, evaluated, and compensated.
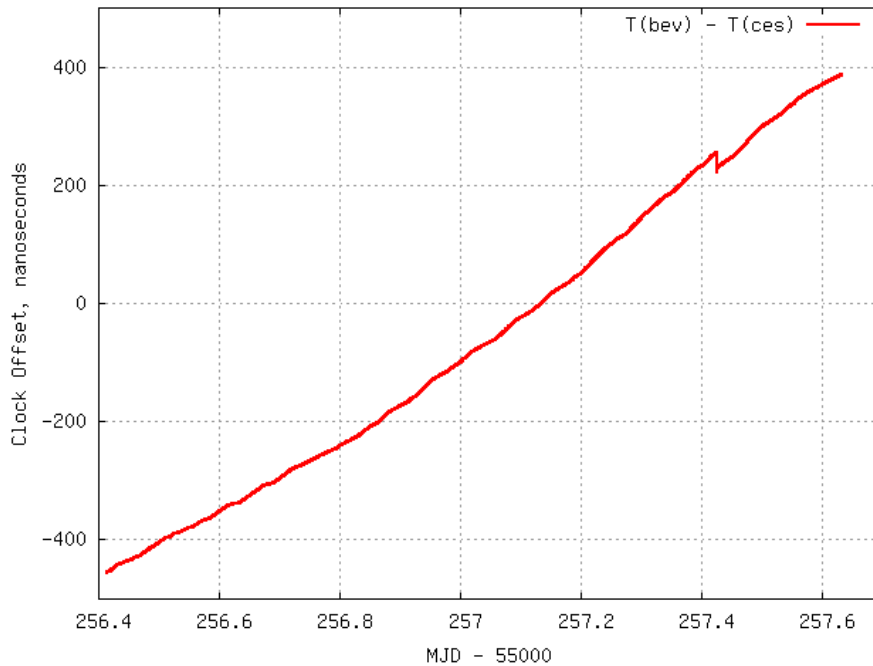

Figure 5. Time transfer between Prague and Vienna.

EXPERIMENT 3 – COMPARISON WITH GPS-BASED TIME TRANSFER

Our intention was to verify optical time transfer and compare the method performance with a standard time transfer device. We used two GPS dual-frequency receivers GTR-50 (GTR-50 is a commercial time and frequency transfer system that is utilized in many time and frequency laboratories). One site of measurement was located in the Laboratory of the National Time and Frequency Standard in the Institute of Photonics and Electronics; the second site of measurement was temporarily set up on the campus of the University of West Bohemia in Pilsen – we installed there a free-running rubidium clock (based on PRS-10 from Stanford Research Systems), a GTR-50 device with a GPS antenna and an optical transfer adaptor. The geographical distance of both sites was 94.1 km, while the optical cable length was 153 km.

Figure 6 shows the time difference between both sites measured by two-way optical transfer and code and carrier-phase Common View GPS. The duration of such measurement is limited by the visibility of one particular satellite (SV 19). Figure 7 contains the same data with frequency drift removed. The time stabilities of two-way optical transfer and CV GPS in terms of Time deviation are shown in Figure 8. For comparison, time stability of our Rb clock measured directly against a Cs clock is also included.

Figure 9 provides the difference of optical transfer and GPS code measurement (from CGGTTS data) during 10 days – the RMS is 0.74 ns. The declared accuracy of GTR-50 measurements is below 1 ns RMS; therefore, the observed difference of both methods is in the range of GTR-50 inaccuracy. Despite this fact, we can observe a daily periodicity caused probably by temperature dilatation of the dispersion
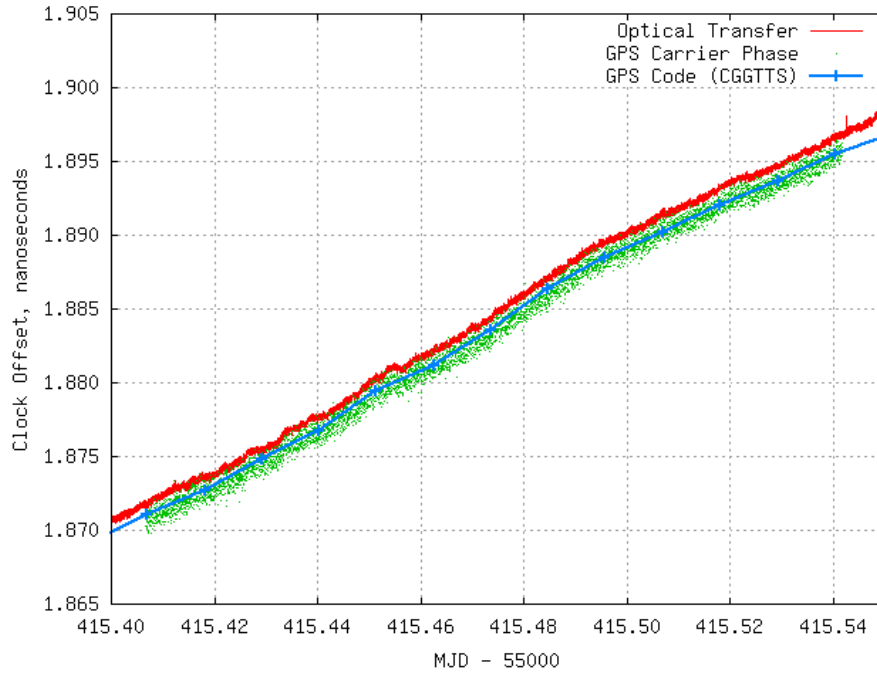
compensation fiber.

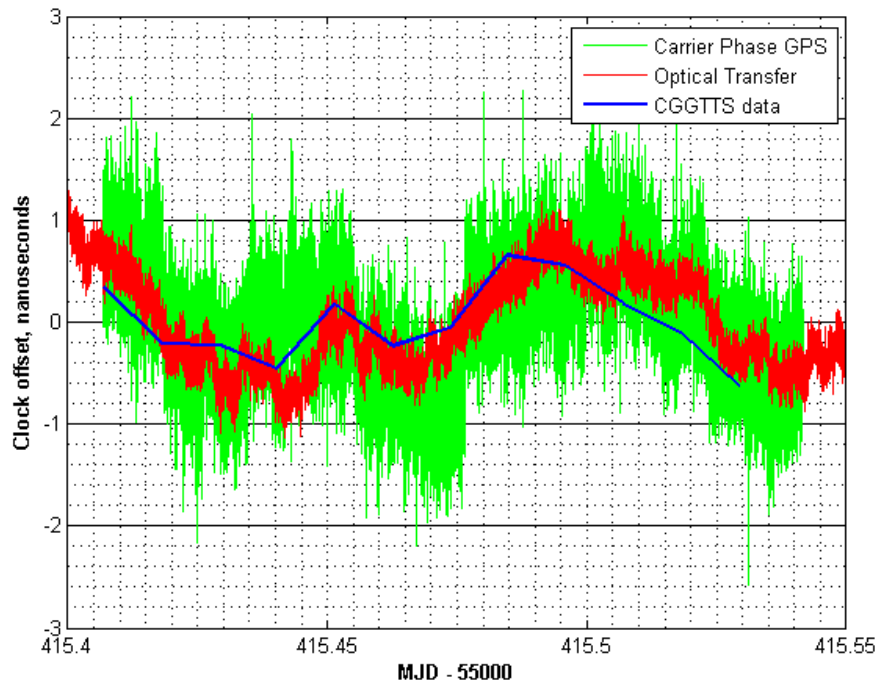Figure 6. Optical and GPS time transfer.

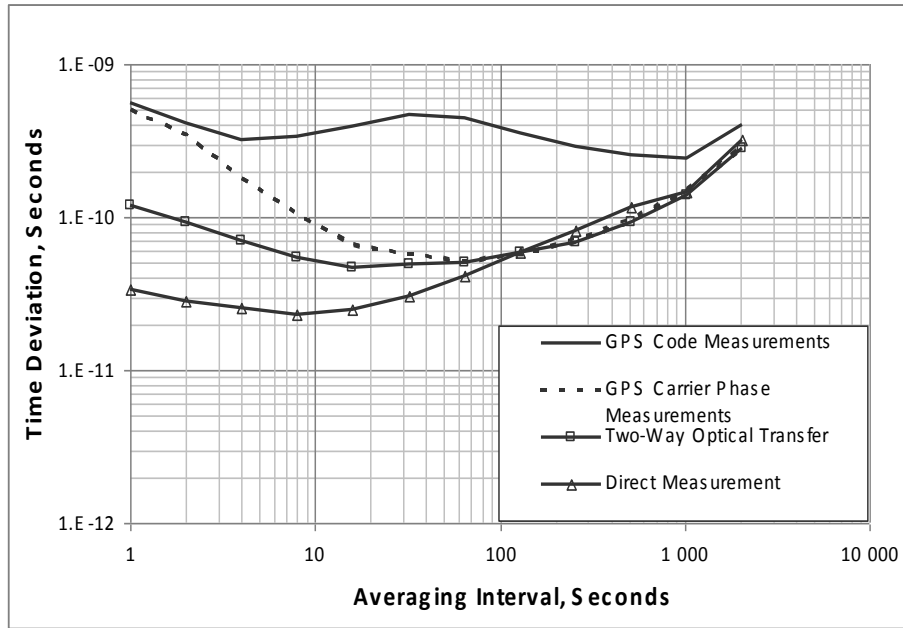Figure 7. Optical and GPS time transfer (without frequency drift).

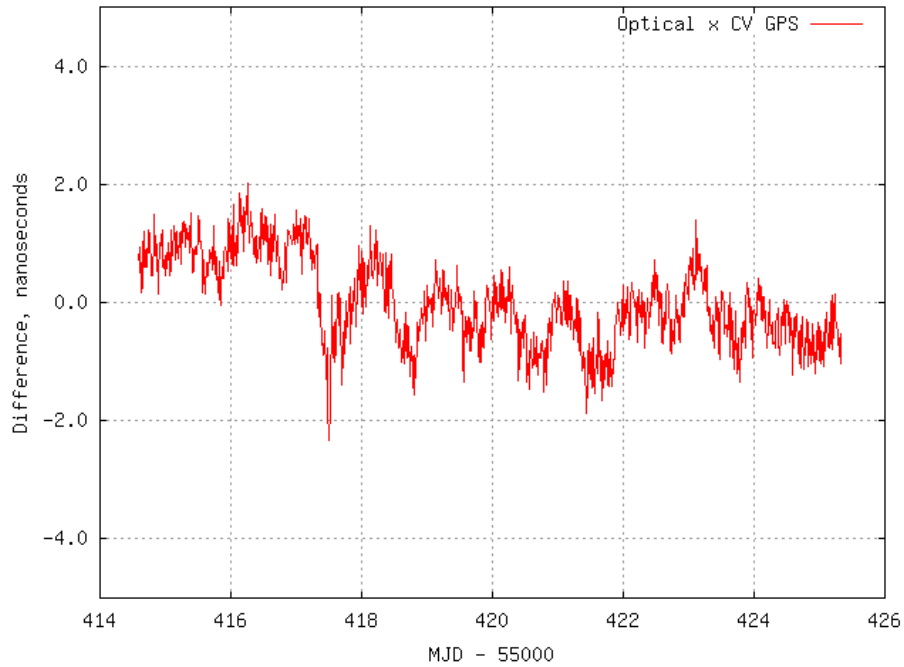Figure 8. Optical time transfer stability.

Figure 9. The difference between optical and CV GPS time transfer.

CONCLUSIONS

We verified the functionality of the method and adapters on time transfer in a 740-km fiber in a real production network and we proved that the system is compatible with DWDM technology and does not interfere with other data channels.

We measured the time stability of the time transfer with minimum value of 8.7 ps in terms of TDEV at an averaging time of 500 s. This value includes all sources of inaccuracy, i.e. the noise in the transmission channel, SFP transceivers, signal modulator/demodulator, etc. We also compared the accuracy of our optical time transfer with Common View GPS time transfer and confirmed that, despite daily fluctuation, the difference is within ±2 nanoseconds.

We plan to continue in time transfer between Czech and Austrian national time and frequency laboratories in order to evaluate long-term properties − this task also takes place under the EURAMET Project #1146.

ACKNOWLEDGMENTS

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