

# COMPARISON OF PRECISE TIME TRANSFER WITH USAGE OF MULTI-CHANNEL GPS CV RECEIVERS AND OPTICAL FIBERS OVER DISTANCES OF ABOUT 3 KILOMETERS

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## Abstract

*In this paper, the precise time distribution with usage of optical fiber is considered. Special 1pps electronic-optic and optic-electronic converters developed by the AGH University of Science and Technology (AGH, Krakow) were examined in different configurations in order to verify their usefulness for time transfer. The measurements were performed using real-world fiber between the Central Office of Measures (GUM, Warsaw) and Polish Telecom (Warsaw) over a distance of about 3 km. Results obtained by direct comparison of 1 pps signals transmitted by these fibers were compared with results obtained from the usage of TTS-2 systems with multi-channel GPS-CV receivers and local direct comparisons. Presented results are satisfactory and allow consideration of the possibility of long-distance direct comparisons with optical fibers in time transfer, taking also into account two-directional time transfer. We share some Polish experience in this field.*

## INTRODUCTION

In 1995, M. Kihara and A. Imaoka reported on time and frequency transfer within SDH structure in an optical fiber telecommunications net [1]. This idea has been investigated further [2-5], however we

propose a different simplified electronic-optical system for time and frequency transfer over optical fibers. In November 2005, a fixed optical fiber connection, equipped at both ends with special electronic-optical converters, was set up between the Central Office of Measures (GUM) and Polish Telecom (TP S.A.) in Warsaw, Poland, over the distance of about 3 km. It was done for telecommunications purposes for transmitting standard time and frequency signals from the national time and frequency standard to the master reference clock which synchronizes telecommunications net. The electronic-optical converters, pairs of devices (transmitter and receiver) for 5 MHz sinusoid signals and pairs of devices for 1 pps signals respectively, have been constructed with high precision by the AGH University of Science and Technology (AGH), achieving very good metrological quality [6]. For their construction, the base technical assumption was not to worsen the given-in-specification stability of standard signals transmitted from commercially available HP5071A cesium clock. In these converters, a simple optoelectronic technique with steering of laser emission and reception of light signal was applied, whereas the SONET (SDH) protocol is not used. The wavelength of light used was 1310 nm. Initial laboratory tests of time and frequency transmission with the usage of these converters showed an rms deviation of time transmission below 10 ps (for measurement of 1pps and a 500 sample size) and a time-phase rms deviation of frequency transmission not greater than 15 ps (for 1 ms intervals and a 200,000 sample size) [7]. Current construction of the converters enables correct transmission up to over 50 km without the necessity to use erbium-doped fiber amplifiers. This allows consideration of precise time transfer with usage of optical fibers beyond SDH structure. Especially, the usage of circulators for two-directional optical links in this configuration, an idea suggested by M. Lipiński (AGH) [8], improves here the possibilities of time transfer considerably.

In this paper, we demonstrate results of our last experiments with time transfer over fiber optical cable compared with the GPS Common View (GPS CV) method and local direct measurements. A two-way optical time and frequency transfer system (here specified as TWOTFT) is also considered in an experimental configuration.

## MEASUREMENT SYSTEMS INVESTIGATED

In order to verify the usefulness of optical fibers equipped with 1pps electronic-optical converters developed by AGH, the following measurement systems were set up and investigated:

- a) First, quasi-direct comparisons with the usage of optical fiber versus GPS CV comparisons using multi-channel time transfer systems TTS-2 with thermo-stabilized antennas (schematic diagram shown in Figure 1). In this case, two different sources of 1 pps were compared and reciprocal noise of UTC (PL) and Clock B was present. This type of configuration was observed between MJD 53831 and MJD 53962.
- b) Second, quasi-direct comparisons with usage of optical fiber versus GPS CV comparisons (schematic diagram shown in Figure 2). In this case, the same 1 pps signal of UTC (PL) was compared in both laboratories. This method eliminates the noise of clocks, except for fluctuations of time propagation of 1 pps signals within the optical lines. This type of configuration was observed between MJD 54003 and MJD 54034.
- c) Quasi-direct comparisons with usage of optical fiber versus typical local direct comparisons (schematic diagram shown in Figure 3). In this case, the same 1 pps signal of UTC (PL) was compared twice in one laboratory. This method eliminates the noise of clocks and allows determination of fluctuations of time propagation of 1 pps signal within the optical lines. This type of configuration was observed between MJD 54003 and MJD 54034 (performed with configuration b at the same time).

d) Two-way optical time and frequency transfer (TWOTFT) (schematic diagram shown in Figure 4). The 1 pps electronic-optical converters were supplemented with circulators. The noise of clocks is eliminated, but the fluctuation of optical fiber delay (in path: Tr1-Rec1) remains. This type of configuration was observed between MJD 54043 and MJD 54053.

The next experimental configuration (not set up yet) will be a system of type d with both ends of the two-way link located in the same laboratory. In such a system, the noise of clocks will be eliminated and the fluctuation of optical fiber delay will be minimized.

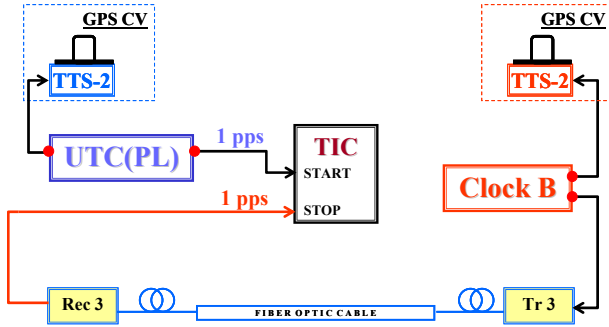


Figure 1. Measurement system for quasi-direct comparison with usage of optical fiber versus the GPS CV method (the noise of clocks is present) – configuration a.

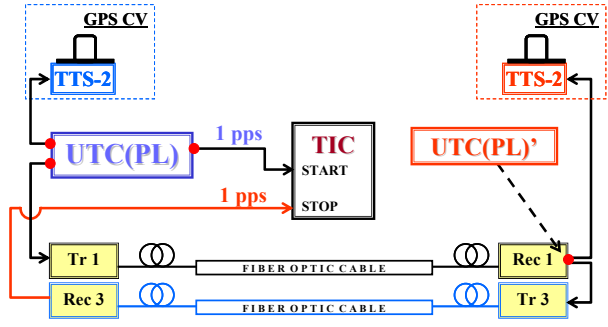


Figure 2. Measurement system for quasi-direct comparison with usage of optical fiber versus the GPS CV method (the noise of clocks is absent) – configuration b.

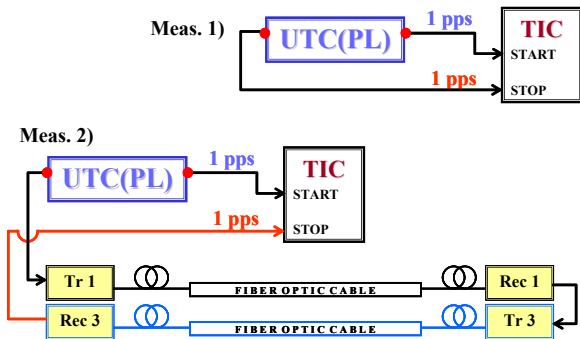


Figure 3. Measurement system for quasi-direct comparison with usage of optical fiber versus typical local direct comparisons (the noise of clocks is absent) – configuration c.

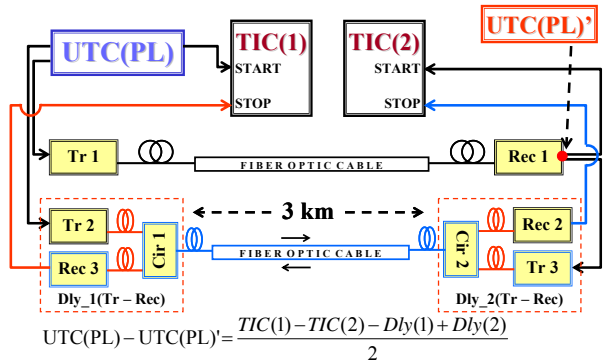


Figure 4. Measurement system for TWOTFT (the noise of clocks is absent) – configuration d.

All measurements with TTS-2 with UTC (PL) as a reference signal as well as with TIC for quasi-direct and local direct comparisons were performed in the Time and Frequency Laboratory of GUM, whereas the measurements with the second system TTS-2 with Clock B or UTC (PL)' as a reference signal were performed in the laboratory of TP S.A. These laboratories were geographically separated by the distance

of a 3-km baseline. Before the first series of measurements, the initial delays of optical paths were determined by measuring the time propagation of UTC (PL) signal transmitted along each optical path and returned along another optical path – three fixed optical lines and three pairs of 1pps electronic-optical converters were the minimum number suitable for such measurements. The delays of each component or each pair of components for TWOTFT at both ends of the optical line were determined as well. Direct local and quasi-direct comparisons were made every 900 seconds.

## INSTABILITIES IN OPTICAL PATHS

The accuracy of time and frequency transfer over optical fibers strongly depends on the stability of optical paths. Among many factors involving changes in delays of optical components, the temperature is a dominant one and causes the most significant changes in the delay of optical fibers. It is caused by the longest time of signal propagation for optical fibers (delays introduced by the electronic-optical converters and circulators do not usually exceed 10 ns, whereas the delays of optical fibers are usually expressed in  $\mu$ s), so even small variations in the long-fiber temperature can result in noticeable changes in the observed total delay of the system. The time of light propagation ( $\tau_{fib}$ ) over optical fiber varies mainly due to temperature variations in the group refractive index ( $n_g$ ) of the fiber, temperature changes in length ( $l$ ) of the fiber as well as in length ( $\lambda$ ) of light emitted by laser and dependence of refractive index on length of light. It can be approximately written as in the formula below:

$$\Delta\tau_{fib} \approx \frac{\partial n_g}{\partial T} \frac{l}{c} \Delta T_{fib} + \alpha \frac{l}{c} n_g \Delta T_{fib} + \frac{1}{c} \frac{\partial n_g}{\partial \lambda} l \frac{\partial \lambda}{\partial T} \Delta T_{LAS}$$

Table 1. Estimated changes in optical fiber delay caused by temperature.

where:

$\Delta T_{fib}$  – change of temperature of optical fiber,

$\Delta T_{LAS}$  – change of temperature of laser,

$c$  – velocity of light in vacuum,

$\alpha$  – coefficient of expansion of optical fiber.

The estimated influence of particular terms for 1310 nm is shown in Table 1.

	Value	$\Delta\tau_{fib}$ for $\Delta T = 1$ K, $l = 1$ km
$\frac{\partial n_g}{\partial T}$	$1.2 \cdot 10^{-5} \cdot 1/\text{K}$	< 60 ps (lab measurements $\approx 30$ ps)
$\alpha$	$5.5 \cdot 10^{-7} \cdot 1/\text{K}$	3 ps
$\frac{\partial \lambda}{\partial T}$	0.1 nm/K	< 3 ps
$\frac{1}{c} \frac{\partial n_g}{\partial \lambda}$	< 3 ps/nm · km	

## RESULTS OF TESTS

In the first and second configuration of measurement system, diagrammed in Figure 1 and 2 respectively, the time difference between 24-hour averages obtained from GPS CV method and from quasi-direct comparisons was analyzed. In order to determine 24-hour averages, the regression lines fitted with the least-squares method were calculated. All delays determined before were introduced and allowed for in calculations. The obtained time differences between both methods are shown in Figure 5, and the rms of dispersion of results relative to regression line for each method are shown in Figure 6. Time differences reaching nearly 8 ns, as shown in Figure 5, are the consequence of summing the changes in the delays of GPS CV equipment and changes in the delay of optical path, which are caused mainly by seasonal temperature variations. Temperature stabilization of antennas does not eliminate this effect. This time difference is also not eliminated in the case of the absence of clock noise; it diminishes with the lowering

of the external temperature. The rms of GPS CV measurements and quasi-direct comparisons, presented in Figure 6, shows the much lower noise of the quasi-direct method relative to GPS CV method; it is especially clearly visible in the period between MJD 54003 and MJD 54034 with the reduced noise of the clocks. Relatively big rms values for GPS CV observations are due, firstly, to the relatively big noise of the clocks and, secondly, to the location of the second TTS-2 system close to high buildings. It results in only 2 to 4 common tracks during one session, whereas the GPS CV link GUM – AOS usually has 7 or 8 common tracks in one session (8-channel system in the GUM receiver) with an rms of about 2 ns calculated analogously.

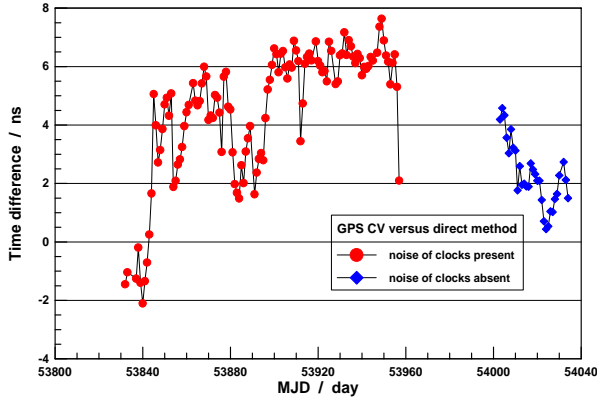


Figure 5. Time difference between 24-hour averages obtained from GPS CV and quasi-direct comparisons with usage of optical fiber (configurations a and b).

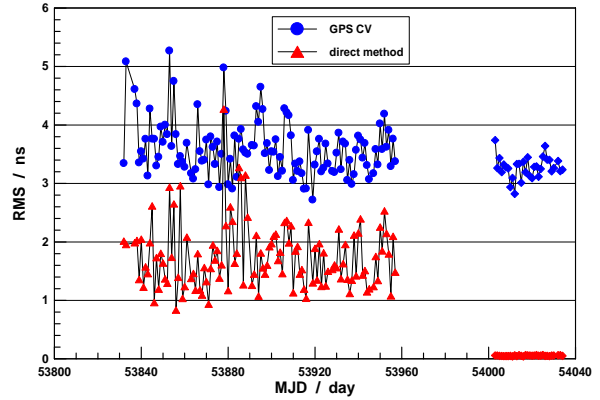


Figure 6. Rms of dispersion of data relative to the regression line for 24-hour periods calculated separately for GPS CV and quasi-direct comparisons (configurations a and b).

Real limitations of the quasi-direct method are observed in configuration c of the measurement system, diagrammed in Figure 3. The results of these measurements are presented in Figures 7 and 8. For 24-hour averages, the rms (see Figure 7) of the quasi-direct method achieves values close to 60 ps, which most probably corresponds to very small variations of fiber temperature in soil (about 1 m in depth). The same parameter for the local direct method achieves values close to and below 30 ps, which is associated with TIC used for measurements. Assuming the values given in Table 1 and the optical path length of approximately  $2 \times 3 \text{ km} = 6 \text{ km}$ , 60 ps refers to the 24-hour temperature variations at the level of  $(0.2 \div 0.4) \text{ K}$ . The dependence on slow seasonal changes in the air temperature and the inertia of changes in the delay of optical path are clearly visible in Figure 8, although the measurements of the soil temperature were not performed.

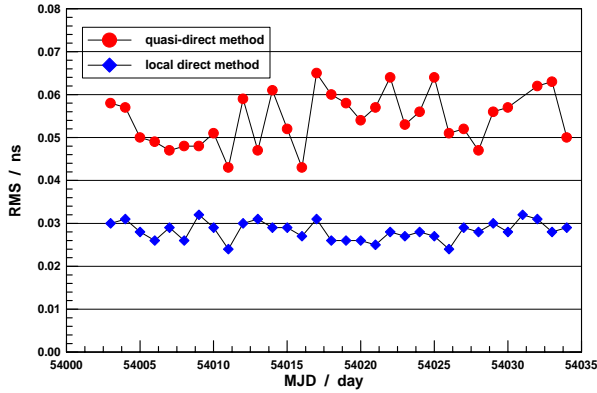


Figure 7. Rms of dispersion of measurement points relative to the regression line for 24-hour periods calculated separately for local direct and quasi-direct comparisons (configuration c).

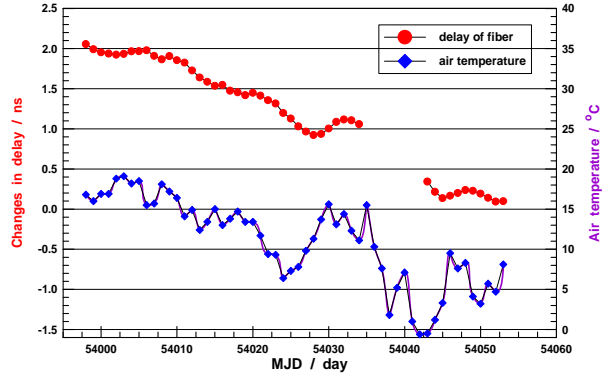


Figure 8. Changes in the delay of the optical path observed during quasi-direct measurements (configurations c and d) and variations of external air temperature.

Time stabilities for the data obtained in the measurement systems investigated are shown in Figures 9, 10, and 11. The diagrams in Figures 10 and 11, for the quasi-direct method and the local direct method respectively, show slightly overly high TDEV for the averaging time below about  $10^4$  seconds due to the adopted time interval between measurements (900 seconds for TIC measurements). In both cases, the rms of a series of 100 measurements with a 1 s time interval, performed during determination of the delays of optical paths or delays of cables, was observed to be below 12 ps, and the overestimated TDEV is here a result of sensitivity of the TDEV statistics to the data density [9]. Some missing data and a not very long measurement time can also deteriorate TDEV [10]. Nevertheless, data densities and data collection periods of compared systems are similar, so these diagrams can be compared.

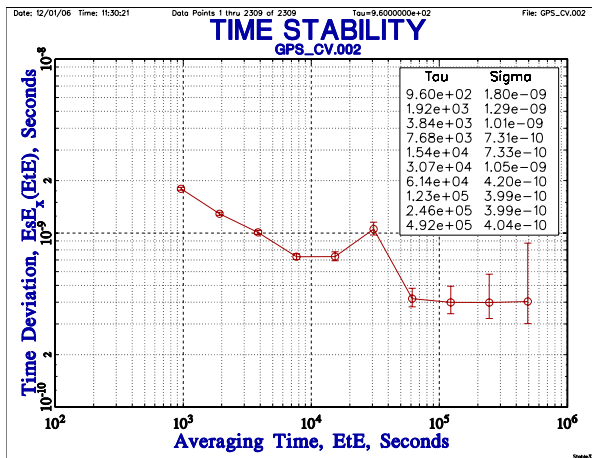


Figure 9. Time stability of GPS CV comparisons (configuration b).

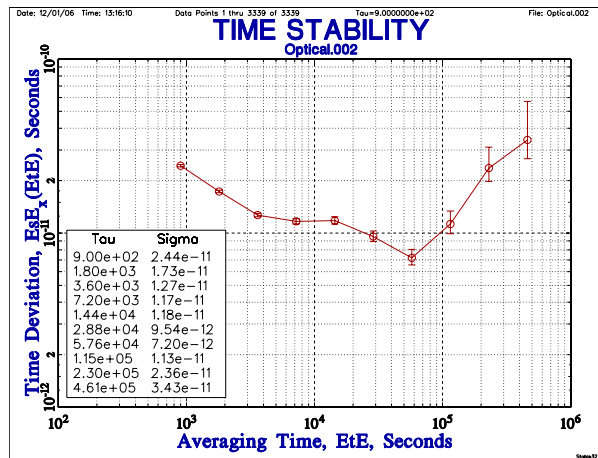


Figure 10. Time stability of quasi-direct comparisons with usage of optical fibers (configuration c).

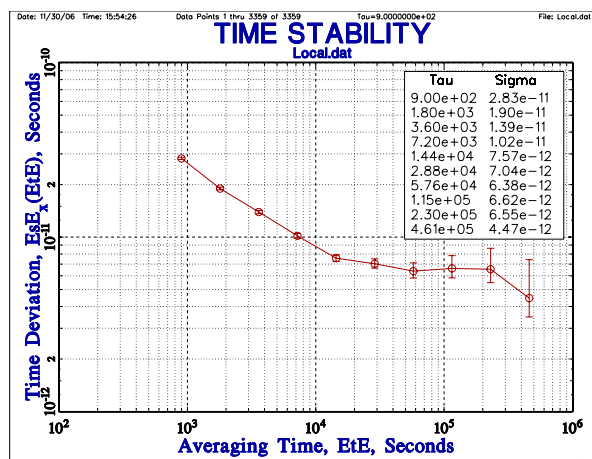


Figure 11. Time stability of the direct local method (configuration c.).

The time stability of the GPS CV method, for measurement data collected in configuration b, is approximately between 10 and 100 times less stable than the time stability in both direct methods, and 400 ps seems to be a limiting value for time transfer stability in this GPS CV link. For quasi-direct and direct methods with TIC, the same limit value is of about 8 ps (50 times better), but for longer averaging periods the external temperature variation results in noticeable worsening of the time stability of the optical link. Peaks observed for about 12 hours in Figures 9 and 10 are diurnal.

For the longer optical link, the greater influence of temperature variations should be expected; however, over a distance of up to at least 10 km, a one-directional optical link should be more stable than a GPS CV link. In order to eliminate or at least minimize the influence of changes in delay caused by the increased length of the optical fiber, TWOTFT should be applied. The work of Celano *et al.* [10] confirmed the possibility of precise timing control using optical fiber over a long baseline. Before full implementation of TWOTFT, the detailed analysis of instabilities in TWOTFT should be verified, as in [4,12,13].

The last configuration of the measurement system, diagrammed in Figure 4, was set up only to check the full configuration for TWOTFT. All devices worked correctly and did not interfere with the work of the remaining ones connected to the same optical line. The initial measurements observed the 24-hour rms as in the case of the quasi-direct comparison – it was the effect of separation of the ends of the TWOTFT link, which involved non-compensated delays of the supporting optical line.

## CONCLUSIONS

The usage of optical fibers equipped with special 1pps electronic-optic converters not only extends the range of direct application of time standard signals, but also allows transfer of time (and frequency) with high precision, preserving the advantages of direct measurements. We showed that the optical fiber link equipped with our converters can transfer time with a stability below 10 ps over the distance of about 3 km, whereas our GPS CV link, equipped with multi-channel receivers, makes possible time transfer with a stability of at least about 400 ps over the same distance. We ran experimental two-directional precise time transfer over optical fiber (TWOTFT) with the use of circulators, and the system worked correctly. Further work is required in order to develop converters for an optical link longer than 100 km, to develop

and determine the real accuracy and stability of TWOTFT, and to provide a more detailed analysis of time stability of all the measurement systems considered above.

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