MULTI-CHANNEL GPS COMMON VIEW TIME TRANSFER EXPERIMENTS: FIRST RESULTS AND UNCERTAINTY STUDY

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Abstract

For regular TAI computations, GPS time transfer is currently carried out using a number of common-view observations from single-channel single-frequency C/A code receivers operating in a scheduled mode. This mode of operation limits the accuracy of time transfer and serious problems of ageing of the current receivers are now being encountered. This paper considers all-in-view measurements from multi-channel dual-frequency GPS time receivers used to carry out time transfer between remote locations, taking into account all possible common-view observations for a given baseline.

We have used data from Allen Osborne Associates TTR-4P receivers operating at the BIPM, the NPL, the ROA and the USNO. Two approaches have been used. First we construct, for each station, standard 13-minute common-view observations of all available satellites and use these data to compute time differences for three baselines. We find that the results are better than those obtained with single-channel receivers, and are about in accord with what might be expected from the number of measurements. Second we use raw short-term data to compute time differences and compare the results with the standard approach for one baseline. We find that the raw data provide a better measurement of the time link than is possible using the standard approach. In all cases the equipment in use display large variations in the calibration delay that are likely to be induced by the environment and require a corrective action.

INTRODUCTION

For about fifteen years, remote clock comparisons have relied on GPS single-channel single-frequency time transfer receivers operated in the common-view mode [1]. Since a few years, progress in clock technology and ageing of the receivers have resulted in the fact that the time transfer technique itself is a limitation for averaging durations of up to a few days. One way to overcome this problem is to use the same basic technique but to expand it using multi-channel (possibly dual-frequency) GPS time receivers and all-in-view measurements so as to make use of all possible common-view observations. This is the subject of many studies [2, 3]. Here we apply this method to one of the available receivers, the Allen Osborne Associates TTR-4P, which provides eight channels with dual frequency.

In this paper we mainly focus on the stability of the time transfer technique. This is represented by the modified Allan deviation, or equivalently by the time deviation $\sigma_x(\tau)$. We do not treat the question of the absolute calibration of the link. We do note, however, that systematic variations in delays present a major problem in the data under study, and would render an exercise of absolute calibration of marginal utility. Methods to overcome these variations will, if successfully applied, result in a stable time link which is then suitable for absolute calibration.

One basic outcome of using multi-channel common-view observations affected by white phase noise, and more generally of using a number of independent measurement points larger by a factor of N, is an improvement in the fractional frequency stability, and therefore in the time deviation, by a factor of $\sqrt{N}$. In addition, the all-in-view approach has the potential to give access to smaller averaging durations than the standard 13-minute approach since the density of successful observations is likely to be larger.

STANDARD MULTI-CHANNEL COMMON VIEWS

The experiment described in this section was performed in August 1997, using TTR-4P units in operation at the National Physical Laboratory (NPL), Teddington, United Kingdom, the United States Naval Observatory (USNO), Washington DC, USA, and the Bureau International des Poids et Mesures (BIPM), Sèvres, France. Though the TTR-4P units operate in a dual-frequency mode, measured ionospheric delays are not generally available; rather the operator must choose to output values of either measured ionospheric delays or modelled ones using the GPS ionosphere model. For this experiment measured ionospheric delays were not available at the USNO, a circumstance which introduces a non-negligible level of noise to the two long distance links involving the USNO.

For each station, the available measurements are raw short-term time transfer data issued from the Block 100 output of the TTR-4P receivers. The sample rate for raw data is chosen by the operator: 10 s for the USNO and 30 s for the NPL and the BIPM. At each station these raw short-term data are processed in order to reconstruct standard common-view results. The treatment is basically the one which is described in the *Technical Directives* recommended by the Sub-Group of the Comité Consultatif pour le Temps et les Fréquences (CCTF, formerly the CCDS) dealing with GPS and GLONASS time transfer standards [4]. The standard common-view results obtained:

- are computed from a linear fit over 78 (10 s) or 26 (30 s) consecutive data and thus correspond to 13-minute averaging times,
- start at dates spaced by 16 minutes, and
- match the common-view grid described in the International GPS Common-View Tracking Schedule as issued by the BIPM.

Observations in which not all 78 or 26 data points were present were not used to avoid a contamination from the noise of Selective Availability.

Due to various factors, including a failure of the TTR-4P unit at the BIPM and gaps in the TTR-4P data at the NPL and the USNO, the data set presented here is somewhat limited. This does not imply that longer continuous intervals cannot be obtained, but is representative of operating problems that seem to appear systematically on some units. Here, 12 days of continuous data (from MJD 50668 to MJD 50679) have been used for the link NPL-USNO, and 6 days (from MJD 50673 to MJD 50679) for the two baselines involving the BIPM. To provide a basis for comparison, data from the single-channel single-frequency C/A code receivers that are regularly received at the BIPM for the computation of TAI have also been used. In addition, data outliers have been removed for all links under study.

For the transatlantic link NPL-USNO, the results can be summarized as follows:
- TTR-4P receivers on both sites, without removal of outliers,
$$\sigma_x(\tau_0 = 514 \text{ s}) = 5.7 \text{ ns}.$$
- TTR-4P receivers on both sites, with removal of approximately 1% of the data
$$\sigma_x(\tau_0 = 521 \text{ s}) = 5.2 \text{ ns}.$$
- Classical receivers, without removal of outliers,
$$\sigma_x(\tau_0 = 4760 \text{ s}) = 5.0 \text{ ns}.$$
- Classical receivers, with removal of approximately 1% of the data,
$$\sigma_x(\tau_0 = 4820 \text{ s}) = 4.2 \text{ ns}.$$

It seems that the deleted data correspond mainly to points with poor broadcast ephemerides, as no editing was required for data computed with precise ephemerides (see below). Curves showing the variation of σ_x with averaging time τ are shown in Fig. 1 for the two computations of the link NPL-USNO after deletion of outliers.

The observed improvement is by a factor of about 2.2 for an averaging duration of about 5000 seconds. As the number of measurements is larger by a factor of about 9, the improvement is less than expected from that effect alone (a factor of 3). One explanation may be that, in the larger data set of the multi-channel receiver, the proportion of data taken at low elevation is larger, and these observations have a larger measurement uncertainty. We note that for longer averaging durations (above 0.5 d) the two stability curves are similar (but slightly poorer for the multi-channel link). This is due to instabilities in the TTR-4P data, and is typical of diurnal signatures linked to environmental variations. It is likely that these instabilities have some effect even for an averaging duration around 5000 seconds, and could also explain why the improvement is only 2.2 for that averaging duration. Such instabilities may also be present in the data from single channel GPS receivers, but these are more difficult to detect because of the level of noise.

In addition, long-distance time links may be improved by using precise ephemerides and measured ionospheric delays. In this case the typical measurement uncertainty is about 3 ns as shown by the regular computation at the BIPM of the links between the Observatoire de Paris (OP), Paris, France, and the National Institute of Standards and Technology (NIST), Boulder, USA, or the Communications Research Laboratory (CRL), Tokyo, Japan [5]. Such an improvement could not be tested here because measured ionospheric delays were not available at the USNO. However, precise ephemerides from the International Geodynamics Service (IGS) have been used and have been shown to slightly improve the stability. For example over a 6-day interval of TTR-4P data, σ_x = 4.4 ns with precise ephemerides (without removal of outliers) and 5.7 ns with broadcast ephemerides (τ_0 = 506 s).

Results for the link BIPM-USNO are similar, but are available over a period of 6 days only so they are not detailed here.

For the short-distance link BIPM-NPL, we find:
• TTR-4P receivers on both sites, without removal of outliers,
$$\sigma_x(\tau_0 = 259 \text{ s}) = 2.3 \text{ ns}.$$

This number cannot be compared directly with that obtained from the classical measurements available from the NPL because the coordinates of the antenna of this particular receiver have an unusually large uncertainty. However, information can be gathered from many time links of similar distance which usually display a measurement noise of about 2 ns [6].

The complete stability curve for the link BIPM-NPL, using TTR-4P units on both sites, is shown in Fig. 2:
• For short averaging durations (up to 5000 seconds), data are affected by white phase noise and the improvement is simply that which corresponds to the increase in the number of measurements. This is a factor of about 3.6 with respect to the maximum number of observations obtainable from a single-channel receiver which tracks continuously (independently of the number of tracks recommended in the International GPS Tracking Schedule issued by the BIPM), and a factor of about 13 with respect to the usual implementation of the schedule, resulting in gains in stability of 1.8 and 3.6 respectively.
• For longer averaging durations, given the good short term stability, the instabilities present in the TTR-4P data are readily observed. They are again typical of large diurnal signatures linked to environmental variations.

SHORT-TERM COMMON VIEWS

This experiment was conducted during four days in October 1997 (from MJD 50724 to MJD 50728) when raw short-term (30 s) time transfer data where available from the TTR-4P units at the NPL and at the Real Instituto y Observatorio de la Armada (ROA), San Fernando, Spain. Unfortunately the set-up of the experiment was not optimal because the receiver at the ROA used measured ionospheric delays while that at the NPL used model ionospheric delays. Nevertheless this feature has little impact on the results of the present study. The data were used first to form time differences directly from the raw short-term data, then standard common-view measurements were reconstructed following the procedure described in the *Technical Directives* [4].

The main results are as follows:
- Short-term common views, with removal of the obvious outliers (about 0.2% of the data),

$$\sigma_x(\tau_0 = 5.9\ \text{s}) = 6.4\ \text{ns}.$$

- Reconstructed common views, with removal of outliers,

$$\sigma_x(\tau_0 = 300\ \text{s}) = 3.8\ \text{ns}.$$

The corresponding stability curves are shown in Fig. 3.

Using only observations at elevations greater than 25 degrees, we find:
- Short-term common views, with removal of the obvious outliers,

$$\sigma_x(\tau_0 = 8.0\ \text{s}) = 4.4\ \text{ns}.$$

- Reconstructed common views, with removal of outliers,

$$\sigma_x(\tau_0 = 366\ \text{s}) = 3.4\ \text{ns}.$$

When comparing the values of σ_x for several averaging durations (see Fig. 3), we observe that the improvement is by a factor of about 2.5 for 300 s, by a factor of about 2 for 1000 s, and that the values are similar for 5000 s and above. We have seen in the previous section that above 5000 s to 10000 s systematic instabilities begin to dominate and, in this particular case, additional noise is due to the fact that one station used measured ionospheric delays while the other one used a model. For shorter averaging durations, the improvement in using raw data is striking.

The improvement results, first from the increased number of data points. We observe that the reconstructed common-view approach results in using only about half the short-term data points. This factor of 2 can be decomposed in three parts. About 20% of the loss is due to the gap in the reconstruction scheme (3 minutes every 16 minutes), and about 30% is lost at each station due to micro-gaps in the data. Indeed, because of Selective Availability, the common-view observations must be reconstructed using all 26 raw data points and the loss of one single point at a single station prevents this reconstructed observation being used. Even though the observed percentage of missing raw data is less than 1 % at each station, the total effect on the number of reconstructed common views is large. In contrast, the number of usable raw time differences is 98.8% of the maximum possible number (not counting one larger gap of about two hours which is common to the two approaches).

A second point is that the detection of outliers is easier in the raw short-term data. Errors in raw data are usually very large and can be identified with very simple filters. This is a significant advantage though not a definitive one: in general, reconstructed common views containing one bad data point can also be identified, although the effect is less obvious.

These two factors can explain an improvement in stability by a factor of about 1.5, but cannot account for the actual 2.5 gain observed. This effect is even more important when an elevation cut-off of 25 degrees is used. Further investigation remain necessary to confirm this improvement and to explain it.

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CONCLUSION

We studied data from multi-channel dual-frequency Allen Osborne Associates GPS time receivers of type TTR-4P, in terms of the stability of time transfer via common views on short and long baselines. We find that, for short averaging durations (up to 5000 seconds), data are affected by white phase noise and the increase in the number of measurements results in a better stability. An even better stability is achieved when using raw short-term measurements, rather than reconstructed standard common-view observations, to compute the time link.

For this particular equipment, the major limitation is systematic delay variations which dominate for averaging durations above 5000 s to 10000 s. Such variations are probably induced by environmental variations at the antenna and are being addressed by techniques such as the thermal stabilization of the complete antenna or of the first amplification stage [7].

Once this major limitation is removed, GPS code measurements are capable of providing a time deviation of less than one nanosecond for an averaging duration of 1000 s and therefore 0.1 ns for one day. The corresponding figures for the fractional frequency stability are about 1×10^{-12} and about 1×10^{-15} respectively. The stability for durations of one day and above is similar to what can be obtained by adding phase measurements [8], but this approach provides better stability for shorter averaging durations.

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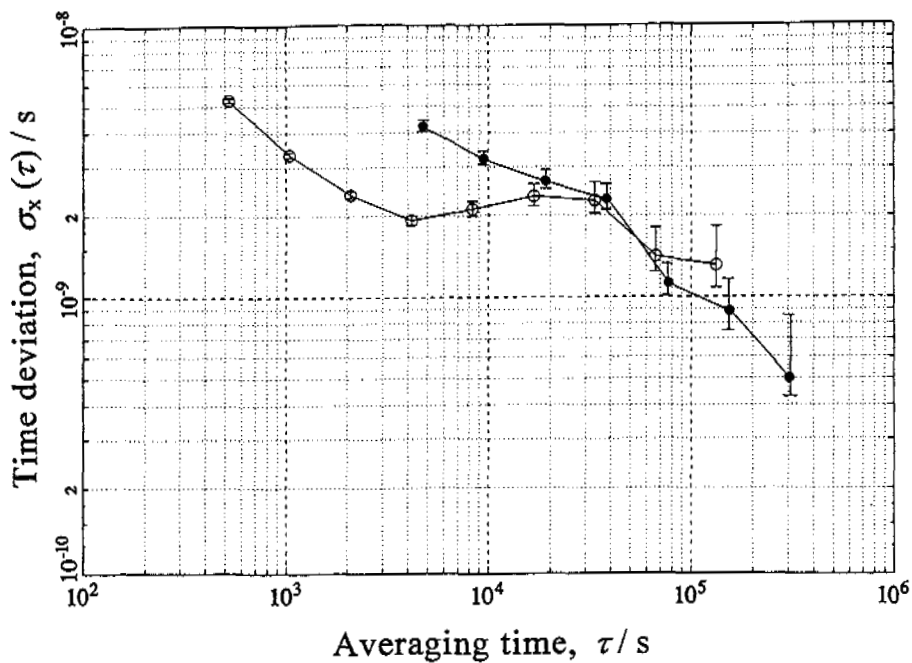
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Fig. 1: Stability curves showing the variation of the time deviation σ_x versus the averaging time τ, for the time link NPL-USNO computed with standard common-view measurements provided by TTR-4P units (○) and classical receivers (●) on both sites.
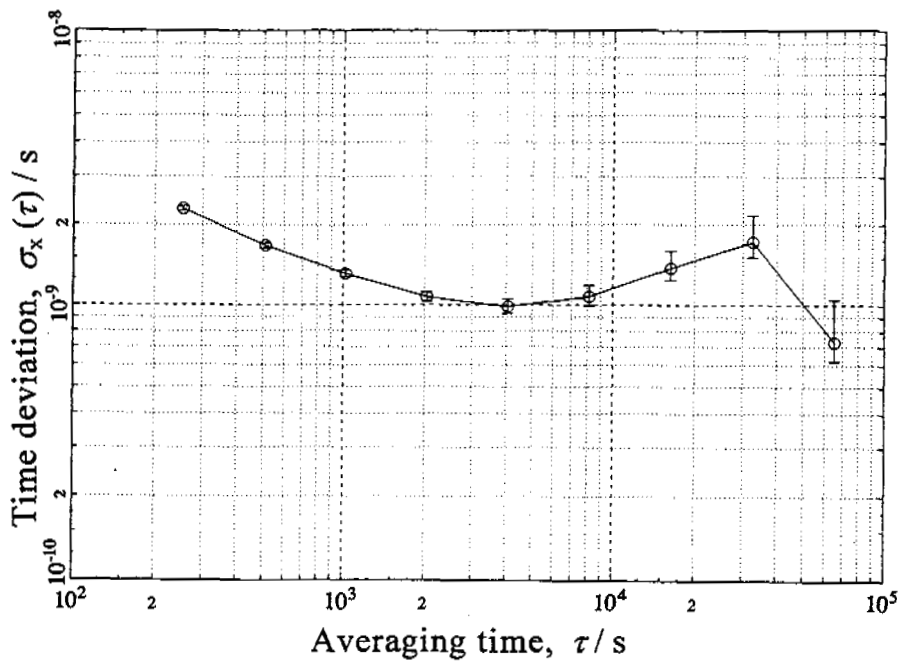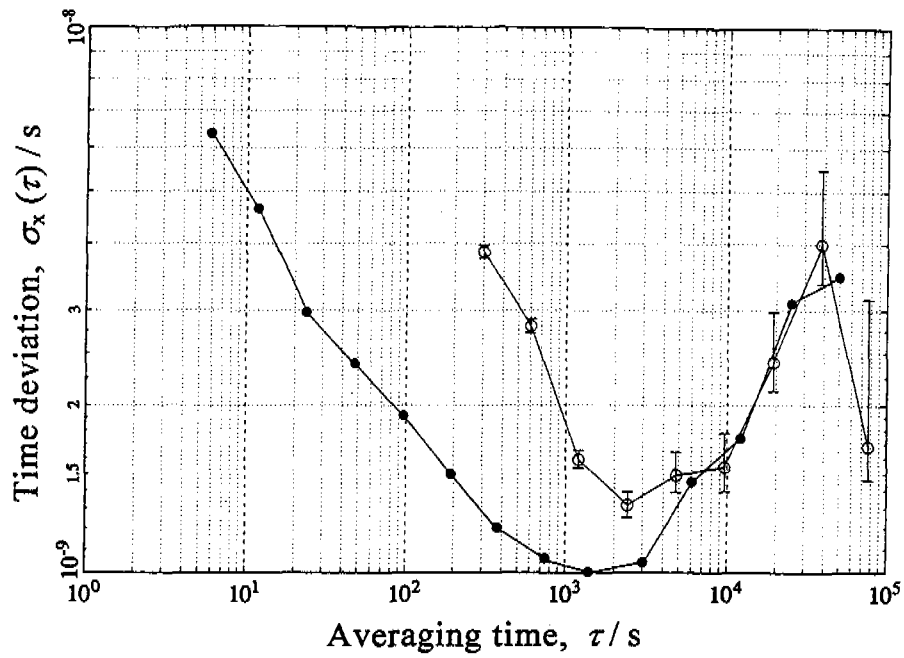

Fig. 2: Stability curve showing the variation of the time deviation σ_x versus the averaging time τ, for the time link BIPM-NPL computed with standard common-view measurements provided by TTR-4P units on both sites.

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Fig. 3: Stability curves showing the variation of the time deviation σ_x versus the averaging time τ, for the time link ROA-NPL computed with short-term (30 s) common-view measurements (●) and reconstructed standard common-view measurements (○) provided by TTR-4P units on both sites.

Questions and Answers

JUDAH LEVINE (NIST): My comment is that the standard analysis method described in the BIPM documents requires one-second measurements. Once you do not have one-second measurements, you can reconstruct the common view, but it is not exactly the same. It averages the SA in a slightly different way because the BIPM method averages SA in a way that is different than the 26 thirty-second measurements. Now, that is not a problem if you compare the identical receivers using the identical method. But it does not necessarily mean that you can compare the new receivers with the old receivers because they are going to average the SA in a different way. That means that once you do not measure every second, I think there is no point reconstructing the BIPM method because you can not compare with the old receivers anyway. That is my bias, my preference; but you understand what I am saying, there is no point in going to 13-minute tracks because you can not compare with the old receivers anyway. Thank you.

GERARD PETIT (BIPM): Yes, you are right. But of course in this case it was similar receivers with similar setups.

JUDAH LEVINE: That is fine.

ROBERT WEAVER (UNIVERSITY OF SOUTHERN CALIFORNIA): I just wanted to share with you something, and with the other speakers who have brought out diurnal variations, probably due to temperature (perhaps other effects); and that relates to cable effects. I see that the use of an oven can take care of the temperature variations on antennas and the pre-amplifier perhaps. In my experience from a previous employment, we ran into cable phase variations that can amount on the order of .1 (point one) percent of the cable length, variations in delay of a cable. So if you have a cable that is 10 meters in length – I do not know what lengths you typically use – but that could perhaps amount to a fairly substantial variation that needs to be taken care of. That is my first point.

The second point is when you look at the effect of temperature on a cable, these effects that one would expect be reasonably linear or quadratic or something with the function of temperature are really not. Many materials that are used as the dielectric, in these cables, have sudden variations in temperature regions that correspond to the properties of the materials that are used as the dielectric. In our case, we were using Teflon dielectric that had a sudden variation around 20 degrees Celsius, or in that general vicinity; and you could have sudden jumps over an interval of perhaps 10 to 20 degrees Celsius where you would get this total variation of around .1 (point one) percent of the length of a cable.

I just want to bring that out as one possible area to look at for the systematic effects of temperature.

ROB DOUGLAS (NRC): That is a very helpful comment. Any other questions?

TOM PARKER (NIST): A comment about the cables. If you use a cable with a polyethylene dielectric, the stability is substantially better, and, in fact, you can get cables that are phase-stabilized and have a parabolic delay versus temperature dependence with a peak right around 20 degrees C.

ROB DOUGLAS: Not a lot of help from Canada these days. Are there other questions or comments? There are some other people in the audience who have multiple-channel timing experience.

WLODZIMIERZ LEWANDOWSKI (BIPM): A few comments about cables: Of course, we have been thinking about cables for a long time, but we have other problems not related to cables. We are now considering very strongly to make a build-up to protect cables from temperature variations and using cables of different materials. At BIPM, we are already considering putting our temperature-stabilized antennas just above the laboratory and build temperature protection for the cables. So, this is an obvious next step to do.

GERRIT de JONG (NMi VAN SWINDEN LABORATORIUM): I think cable is a secondary problem compared to the filters which are now included in the antenna path, in the active antenna especially, of course. It is mainly the filter, and also the amplifier contribution; but I think the first thing to do is to stabilize the temperature of the filter which is inside active antennas. Thank you.

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GERARD PETIT: Yes, you are right. We have to treat the problems in the order in which they appear. It seems that now the antenna problem is being corrected, so cable is the next issue.