# A GPS Carrier-Phase Aided Clock Transport for the Calibration of a Regional Distributed Time Scale

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*Abstract* — **Clock transportation is a historically proven time transfer method for the calibration of time links and time scales. With the establishment of satellite-based time transfer methods, however, clock transportation has become less attractive especially on long baselines. In order to match for instance the GPS common view time transfer method with calibration uncertainties of a few nanoseconds, it is necessary to transport high quality, expensive clocks such as caesium beam frequency standards. The stability of the clock during transportation and the duration of the transport set the limit of the prediction uncertainty. Being able to measure the clock during transportation instead of predicting it would yield some major advantages: (a) the use of less expensive and small clocks such as rubidium or quartz oscillators for transportation, (b) no need for environmental conditioning of the transported clock, and (c) the duration of the transport is not critical as long as the clock can continuously be measured. One solution to the clock measurement problem during transport is the use of GPS carrier-phase observations as described and evaluated in this paper. It is shown that a calibration uncertainty of less than one nanosecond is potentially achievable.**

## I. Introduction

GPS time transfer is an important and commonly used method for the comparison of clocks and time scales maintained at sites separated by a long distance, and for many applications involving accurate time dissemination there is a need for an accurate relative calibration of the GPS-equipment established at both sites. Historically, such calibrations were performed using the method of transporting/traveling clocks. This method has, however, in principal lost its practical use due to the difficulty of predicting the transported clock's time drift during the transportation accurately enough for today's metrological requirements.

As the calibration accuracy is limited by the stability of the transported clock during the transportation, the achievable accuracy is limited to the order of **tens of nanoseconds** and requires the transportation of expensive and delicate clocks such as caesium clocks in order to reach this level. Today, relative site calibrations are therefore often achieved by transporting reference GPS-equipment instead. Here the achievable accuracy is usually limited to **a few nanoseconds** due to the use of GPS code measurements. For widely separated sites this method is still the only practical method. However, for sites separated by a shorter distance, for instance within a region of a country, a combination of clock transport and GPS may be beneficial.

This paper describes a GPS carrier-phase aided clock transport for the calibration of a regional distributed time scale and a (GPS) time link between the national time and frequency laboratory at SP Technical Research Institute of Sweden and the time facility at Onsala Space Observatory (OSO) at the Chalmers University of Technology in Sweden. Both sites maintain a number of atomic clocks and individual representations of the national time scale of Sweden, UTC(SP). The sites are separated by a distance of about 70 km and are routinely compared using GPSP3 [1].

The suggested method continuously estimates the relative time drift between the traveling clock and the stationary clocks, in this evaluation the stationary time scales maintained at SP and OSO. At both stationary sites, the GPS carrier-phase derived phase offsets between the traveling clock and the stationary clocks are fitted to overlapping local time interval measurements between the respective clocks, yielding a time series of the absolute phase offset between the stationary clocks. In a previous study [2], this method was evaluated by a local round-trip rubidium clock transport from and to SP. The results suggested that **sub-nanosecond** calibration is potentially achievable if special care is taken to control the environment around the traveling GPS-equipment. It showed the ability of tracking the phase of the transported clock with high accuracy. Thus relatively cheap and robust clocks may be used.

The results presented in this paper further evaluate the method by GPS carrier-phase aided one-way transportation of a caesium clock between SP and OSO. The method is described in more detail in Section II. In Section III, the results of this evaluation are reported. Section IV contains a discussion and conclusion of the results and some suggestions for future experiments.

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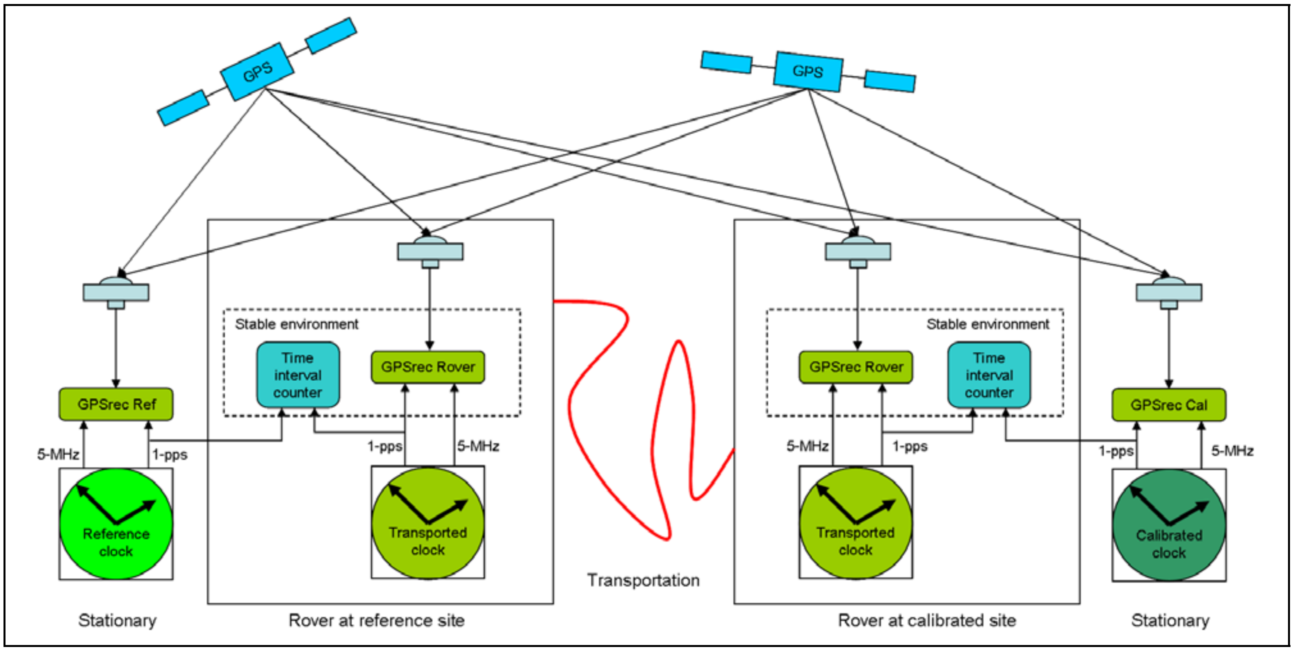


Figure 1. The principle of the GPS carrier-phase aided clock transport method. The reference clock to the left is connected to the stationary reference GPS-receiver. The clock to be calibrated, to the right, is connected to the stationary GPS-receiver at the calibration site. The transported clock is connected to the rover GPS-receiver and measured and related to the reference clock during transport using GPS carrier-phase L3 observations. The time interval counter is a part of the transported equipment and is located together with the rover GPS-receiver in a temperature-stabilised box. For this experiment the reference clock is located at SP and the calibrated clock at the Onsala Space Observatory (OSO). The transported clock was a caesium beam frequency standard. The driving distance between the two sites was around 100 km.

## II. Description of Method

Fig. 1 depicts the principle of the GPS carrier-phase aided clock transport method. All involved GPS-receivers track all satellites in view during the complete transportation. Further,

- in a pre-phase, the transported clock is compared with the reference clock using a time interval counter (TIC),
- in all phases of the transport, GPS carrier-phase L3 observations of the reference receiver and the rover receiver are used to track the drift of the transported clock relative to the reference clock,
- in a post-phase, the transported clock is compared with the clock to be calibrated using the same TIC as in the pre-phase, and the comparison is corrected for the GPS carrier-phase estimated time drift of the transported clock.

As understood, the stability of the transported clock is of less importance as long as it can be measured and its time drift can be related to the reference clock. The instability due to the environment of the TIC and the rover GPS-receiver is more critical and thus this equipment needs to be located inside a temperature-stabilised box for best performance. Alternatively, but less stringent, this equipments ambient temperature can be measured and component delay changes could be modelled. The cables connected to the TIC are brought along with the transport so as to minimize any offset in the pre- and post-phase TIC-measurements and, if possible, no extra cables should be used.

**Calibration of time scale:** The GPS carrier-phase L3 measurements have an undefined but arbitrary offset relative to the "absolute" TIC-measurements. The first step in the comparison is to align the common GPS- and TIC-measurements in the pre-phase to zero average as

$$[CL_{ref} - CL_{tra}]_{TIC\text{-}pre} - [CL_{ref} - CL_{tra}]_{GPSL3} + C_{arb} = 0 \quad (1)$$

where $C_{arb}$ is the arbitrary offset. If the GPS carrier-phase is continuously tracked during the transport, the time transfer is achieved in a second step by comparing the GPS-measurements with the TIC-measurements in the post-phase as

$$[CL_{ref} - CL_{cal}]_{GPSL3+TIC\text{-}post} = [CL_{ref} - CL_{tra}]_{GPSL3} + C_{arb} - [CL_{cal} - CL_{tra}]_{TIC\text{-}post} \quad (2)$$

**Calibration of time link:** In order to calibrate the GPS time link of the stationary receivers, the estimates of the stationary time link is compared to (2) as

$$[CL_{ref} - CL_{cal}]_{GPSL3P3} - [CL_{ref} - CL_{cal}]_{GPSL3+TIC\text{-}post} = C_{cal} \quad (3)$$

where $C_{cal}$ is the wanted calibration constant of the link. It is needed, of course, to adjust the GPS carrier-phase L3 observations of the stationary link with the P3 code data.

Figure 2. Experimental setup. Top: Dorne-Margolin choke-ring antenna on top of rover. Middle left: The rover at OSO. Middle right: The TIC and the rover GPS carrier-phase receiver inside the box. B: Temperature-stabilised box on top of carry inside rover and transported caesium clock below.

## III. Evaluation and Results

As mentioned in Section I, the method was first evaluated a few years ago in a round-trip sense by comparing a rubidium clock to UTC(SP) before and after transportation. The results obtained show a potential of less than 1 ns uncertainty in the calibration of remote time scales [2]. The present experiment was conducted on January 22, 2009 between SP Technical Research Institute of Sweden and Onsala Space Observatory (OSO), see Fig. 2. The driving distance between the two sites was approximately 100 km. In addition to evaluating the method, the aim of the transport also was to deliver a caesium beam frequency standard to OSO and at the same time calibrate the time scale realised at OSO and the GPS time link between SP and OSO. The transported clock was thus a caesium beam frequency standard. The two time scales realised at SP and OSO are based on Hydrogen masers. The transport started at SP and ended at OSO. However, in order to verify the processing of the rover GPS carrier-phase L3 observations, the clock was again transported back to SP after the end of the experiment in a round-trip closure sense.

Figs. 3-6 show the result of the transport. The graphs show the time difference between the reference clock at SP and the transported clock as [$CL_{ref}$ - $CL_{tra}$] compared in different ways during the experiment. Fig. 3 shows the complete transportation with the pre-phase, transport phase, post-phase, following by the (additional) verification phases containing the return transport and the test-of-closure phase. The GPS carrier-phase L3 processing between the rover GPS-receiver and the reference GPS-receiver at SP was performed using in-house software as described in [2]. The combined GPS code P3 and carrier-phase L3 processing between the two stationary receivers was performed using the GIPSY-OASIS software package [3].

Fig. 4 is a close up of the pre-phase with the alignment to zero average of the pre-phase TIC-measurement and the estimates based on GPS carrier-phase L3 observations according to (1). The agreement between the two different

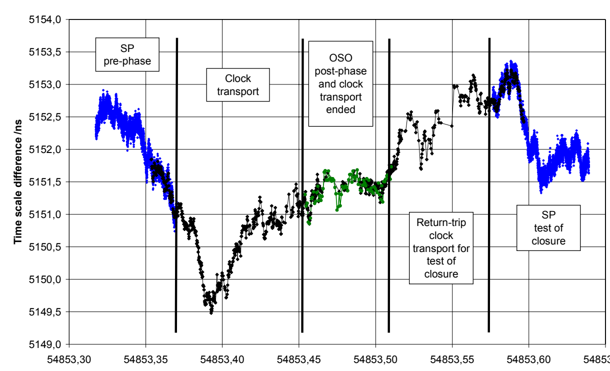


Figure 3. Results of the clock transport. The graph shows the time difference between the reference clock at SP and the transported caesium clock during the complete transport. The different curves are from different analysis according to: blue curve is from the TIC-measurements taken at SP; black curve is from the GPS carrier-phase L3 analysis of the reference GPS-receiver at SP and the rover GPS-receiver; green curve is from the TIC-measurements taken at OSO and the GPS P3 code- and L3 carrier-phase analysis of the stationary receivers.

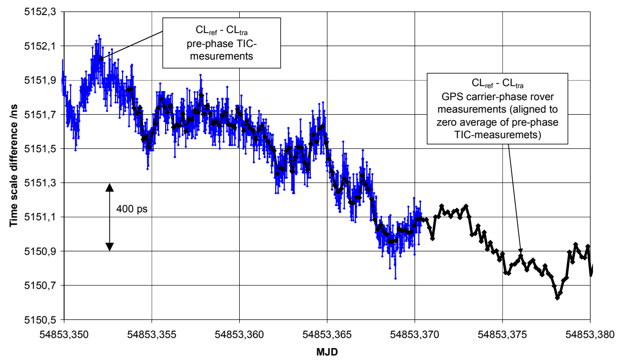


Figure 4. Close up of the pre-phase. Alignment to zero-average of the pre-phase TIC-measurements and the GPS carrier-phase L3 observations accoring to (1). The alignment constant $C_{arb}$ is arbitrary with an rms-difference between the two measurements of about 60 ps.

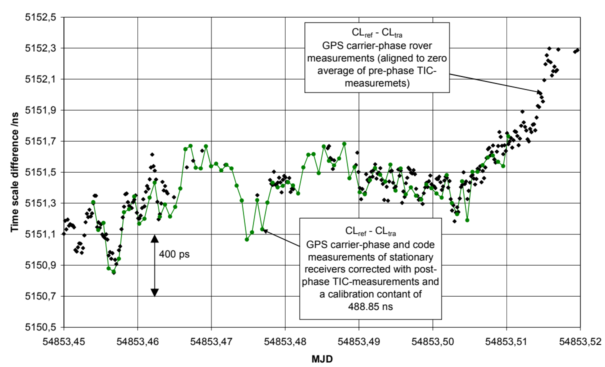


Figure 5. Close up of the post-phase. Alignment of the post-phase TIC-measurements corrected for the GPS P3 code and L3 carrier-phase observations of the stationary receivers according to (2) and (3) in the text. This alignment gives a measure of the calibration constant of the stationary GPS-system at OSO. The estimated offset is 488.85 ns and the rms of the alignment is less than 150 ps.

solutions after the arbitrary constant $C_{arb}$ has been removed is very good with an rms-difference of about 60 ps. This alignment is fixed throughout the transport and is in the end verified by the test of closure.

Fig. 5 is a close up of the post-phase with the alignment of the post-phase TIC-measurements corrected for the GPS P3 code and L3 carrier-phase estimates of the stationary receivers according to (2) and (3). This alignment gives a measure of the P3 calibration offset of the GPS time link between SP and OSO. The offset is estimated to 488.85 ns and the rms-difference between the two solutions is less than 150 ps.

At this phase, the actual clock transport is completed. As mentioned above, however, for evaluation purposes a trip back to SP was made. The trip back to SP gave an opportunity to verify the somewhat complicated task to process the rover's GPS-data. Fig. 6 shows the difference between the TIC-measurements and the GPS carrier-phase L3 observations made at the return to SP. This difference is based on the alignment offset $C_{arb}$ done in the pre-phase shown in Fig. 4. The offset in Fig. 6 between the two data sets is less than 25 ps with an rms of 61 ps. This final result verifies that the GPS

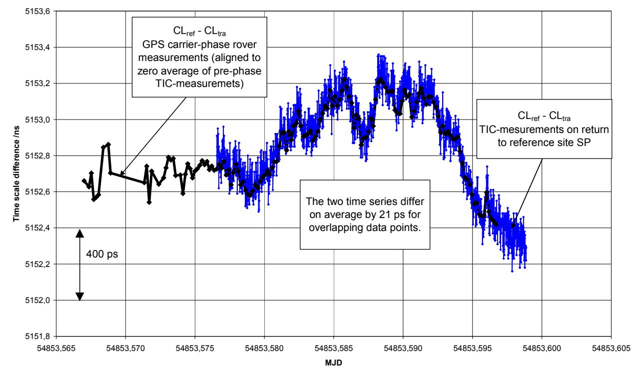


Figure 6. Close up of the closure difference between the TIC-measurements at the return to SP and the GPS carrier-phase L3 observations. This difference is based on the alignment done in the pre-phase shown in Fig. 4. The offset in Fig. 6 between the two data sets is less than 25 ps with an rms of 61 ps. This final result verifies that the GPS carrier-phase L3 processing of the rover GPS-receiver was quite successful and that the TIC and rover GPS-receiver were not significantly affected by temperature variations during the transport.

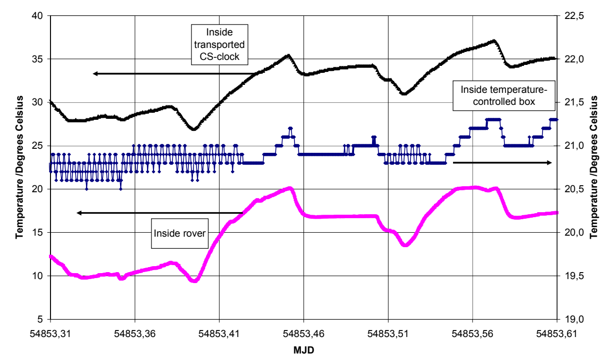


Figure 7. Temperature measurements during the transport. It can be seen that the temperature inside the transported caesium clock follows the temperature changes in the rover, while the temperature in the box with the TIC and the rover GPS-receiver stays within 1 degree Celsius.

carrier-phase L3 processing of the rover GPS-receiver was successful.

The offset in Fig. 6 is also dependent on the temperature variation in the stabilised box. In Fig. 7 it is seen that the temperature inside the box stays within 1 degree Celsius while the temperature in the rover varies by more than 10 degrees. In [4], the temperature dependence of the type of GPS-receivers used in this evaluation was shown to be of the order of 100 ps/K. Representative points of pre- and post-phase in Fig. 7 of the temperature inside the stabilised box differ by around 0.25 degrees Celsius. This would yield a time drift in the GPS-estimates due to a delay change in the transported GPS-receiver of the order of 25 ps, which is of the same order as the offset seen in Fig. 6.

## IV. Discussion and Conclusion

The uncertainty in the calibration of the time scale depends on (a) the TIC-measurements in the pre- and post-phases including the precision and accuracy of the TIC itself, the stability of the support cables from the clocks to the TIC and on the temperature stability of the TIC, and (b) on the GPS carrier-phase L3 processing including noise in the carrier-phase L3 observations and on the stability of the rover GPS-receiver during transport. It also depends on the ability in the rover GPS post-processing of finding the correct integer cycle ambiguities at L1 and L2 as described in [2], which is mandatory to achieve an accurate calibration. Based on this second evaluation of the method, we believe that a calibration uncertainty of less than 1 ns is achievable also for baselines of 100 km and longer.

The critical task is to be able to keep the carrier-phase of the rover GPS-receiver continuous during the transport, independent on signal interruptions - a task that must be handled in the post-processing of the data. In the present experiment, manual and time consuming work was needed to sort out some of the interruptions. In order to make the method more practical, in principle all post-processing needs to be automatic and thus less time consuming. Experiment on optimal settings for kinematic applications of the rover GPS-receiver is strongly suggested.

It is in principle possible to keep the accuracy of the calibration between the two time scales to less than 1 ns by continuously processing the carrier-phase observations of the stationary receivers without relying on code observations. This would be useful for instance in applications in which a comparison of time scales over the periods of weeks up to a few months is necessary.

Finally, the equipment needed in the rover should be smaller and less expensive to make the method more practical. This is obtainable using small scale rubidium or quartz oscillators which need to be integrated in upcoming experiments.

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