FREQUENCY TRANSFER USING GPS: A COMPARATIVE STUDY OF CODE AND CARRIER PHASE ANALYSIS RESULTS

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Abstract

This paper investigates the use of GPS codes and carrier phases for frequency transfer applications. Three types of baselines have been studied. First, the noise of the code and phase methods has been evaluated using a zero-baseline with two geodetic GPS receivers driven by the same H-Maser clock, or by a cesium and an H-Maser clock respectively. From the common frequency reference we were able to derive a frequency stability of 6.10^{-16} for averaging times of one day.
The different response of the hardware of the two receivers to small identical temperature variations is emphasized; the differential effect is about 30 ps/°C. The difference between the L_1 and L_2 carrier phase delays is shown too.

Secondly, on-site tests over a 95-m baseline allowed checking the influence of combining two antennae/receivers in different environments. In this case, the effect of the varying temperature on the hardware delays of the receivers and cables is shown; this effect limits the frequency stability to 6.10^{-15} for an averaging time of one day. The possibility to obtain frequency stabilities of a few parts in 10^{16} is shown; this can be reached if all the instruments are located in temperature-stabilized rooms.

Finally, the frequency stability obtained with different code methods is compared on a longer baseline (640 km) between Brussels and Wettzell. In particular, the influence of using IGS satellite ephemerides instead of broadcast ephemerides is shown to be very small. The "all-in-view" methods based on the code, as well as on the carrier phases, are compared to the classic frequency transfer by common view. Preliminary results, using carrier phases, lead to a frequency stability of a few parts in 10^{15} for averaging times of one day. Again, the main limitations are the hardware delay variations due to the changes in ambient conditions.

INTRODUCTION

The Royal Observatory of Belgium (ROB) is one of the few Time Laboratories which is also actively involved within IGS. On one hand, the ROB time laboratory participates in the realization of TAI and on the other hand, the ROB GPS station belongs to the IGS network. Moreover, GPS analysis is done routinely within the frame of the IGS Regional Densification Pilot Project as one of the EUREF local analysis centers [1].

We have taken advantage of this rather unique collocation to study the use of multi-channel geodetic GPS receivers for time transfer applications. These receivers acquire phase and code observations from all satellites in view, and at both L_1 and L_2 frequencies. Our second goal was the evaluation of the critical aspects of the present setup of the IGS receiver BRUS, driven by a hydrogen maser, to contribute to the BIPM/IGS Pilot Project [5].

It is known that the carrier phases cannot provide an absolute time comparison between the internal clocks of the two receivers; this is due to the unknown phase ambiguity which is inherent to all phase observations. However, a combined use of the code and phase observations can provide the necessary information about the absolute time difference, with a typical precision of 50 ps for 1 day observation [2]. In this paper, we investigated only the frequency transfer results obtained using either the codes or the carrier phases. As a consequence, a constant time offset has been subtracted from the computed time differences.

We have set up a test network at the ROB to perform zero- and short-baseline analyses (see Figure 1). In a first laboratory, two receivers named BRUS (ROGUE SNR-12 RM) and BRUR (ROGUE SNR-8000) were installed. The laboratory is not perfectly air-conditioned. The 12-channel GPS receiver (BRUS) belongs to the IGS network. The two receivers are connected to the same antenna (Dorne Margolin T), which allows performing the zero-baseline experiments. In a first test, both receivers use a common frequency reference from a passive H-Maser clock, and in a second test, the receiver BRUR uses the frequency provided by a cesium clock (HP5071A) rather than from the H-maser clock.

In order to perform short-baseline experiments, a third GPS receiver (ROGUE SNR-8000) is located in another laboratory, where the temperature is not controlled and varies together with the outside temperature. This receiver, called BRUE, is fed by the same H-maser clock as BRUS, and is connected to a Dorne Margolin T antenna located at a distance of 95 meters from the first one.

The longer baseline experiments are performed using the GPS observations of two IGS stations: Brussels (with the receiver BRUS fed by an H-maser clock) and Wettzell (where the receiver is a ROGUE SNR-8000 also fed by an H-maser clock); the distance between the two stations is about 640 km.

In the present paper, we use this setup to investigate which environmental effects influence the signal delays within each type of analyses. The differential delay fluctuations on L_1 and L_2 signal paths, caused by temperature variations in the laboratory where the receivers are located, are also evaluated.

Note that in each case, we computed the synchronization errors between the clocks, as seen from the receivers themselves. These synchronization errors do not correspond to the difference between the external clocks only, but include also the effects of the antenna, receiver, cable,and amplifier delays. The external clocks can only be compared if the relation between the internal receiver clock and the external clock is known.

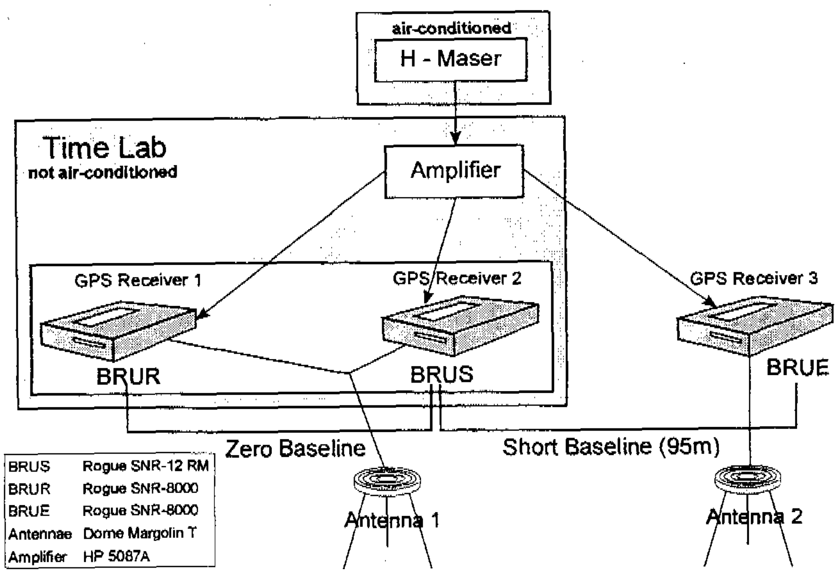

Figure 1: Set-up used for the on-site tests (zero baseline and 95-m baseline).

All computations with GPS code and carrier phase observations have been partially done with the Bernese 4.0 geodetic analysis software [6]. However, since the present version of this software does not comprise a time and frequency transfer module, we made the necessary modifications to the Bernese source code and developed some additional programs which allowed us to obtain the results described in this paper.

ZERO-BASELINE EXPERIMENT

The zero-baseline setup, with the same H-maser clock feeding both receivers (BRUS and BRUR), isolates the effect of receiver hardware delay variations on the results. Figure 2 compares the clock differences obtained with the C/A-code (Fig 2.a) and L_1 carrier phases (Fig 2.b).

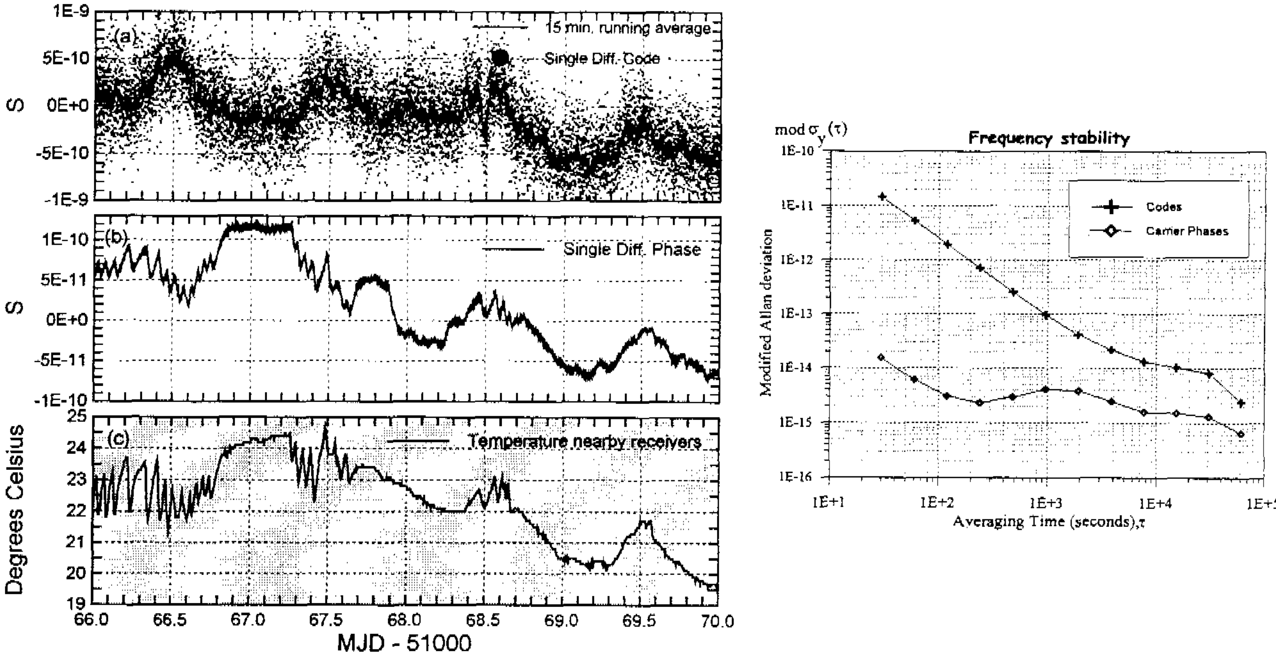

Figure 2: Time differences (H-maser - H-maser) and frequency stability analysis for a zero-baseline experiment where both receivers are driven by the same H-maser clock frequency.

The noise of time differences computed from the carrier phases (a few ps) is about 100 times smaller than the noise of the code analysis. We observe a significant correlation between the phase single differences and the temperature variations in the laboratory (Fig. 2.c).

Thanks to the setup of the experiment, the main component responsible for this correlation could be identified as the different sensitivity of both receivers to ambient temperature variations; this leads to an approximate differential temperature coefficient of about 30 ps/°C for the carrier phase signal path. It is interesting to note that for the C/A-code signal path, the variations of the signal delay seem to be anti-correlated in the beginning of the test and correlated with the temperature at the end of the test. At the time of the writing, the cause of this is not yet clear.

The results emphasize the need to locate the receivers in temperature–controlled rooms, as already pointed out by different authors ([2], [3], [4]).

In a second step, the H-maser frequency driving BRUR was replaced by a cesium clock (HP5071A) frequency. The results for the time differences between both local clocks, deduced from GPS code and phase analyses, are shown in Figure 3. They are also compared with the time differences measured directly from a time-interval meter.
It is clearly demonstrated that the carrier phase analysis does not improve the results obtained with codes, because we are limited by the frequency stability of the cesium clock (given by the curve obtained for mod $\sigma_y(\tau)$). Furthermore, the effect of temperature variations on the delay of different hardware components are not visible in this case, again due to the noise of the cesium clock for averaging times shorter than one day.

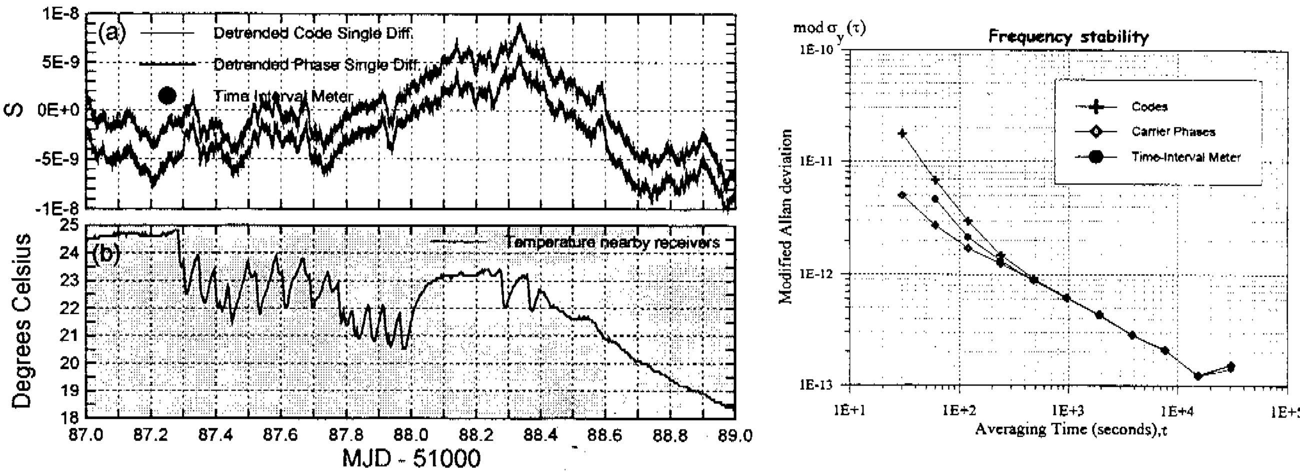

Figure 3: Time differences (H-maser - HP5071A cesium clock) and frequency stability analysis for a zero baseline experiment where one receiver is driven by the H-maser clock frequency and the other one is driven by the cesium clock frequency.

DIFFERENTIAL L1/L2 EFFECT

To compare the effect of temperature variations on the L_1 and L_2 signal path delays, we have used a zero-baseline configuration where one of the two receivers (namely BRUR) was placed in a well climatized room, where the temperature variations were kept smaller than 0.2°C. We considered the hardware delays of this receiver constant. The other receiver (BRUS) was subject to temperature variations as shown in Figure 4.c, resulting in variations of its L_1 and L_2 carrier phase delays. The delay variations are not identical for both carriers. This is due to the fact that the L_1 and L_2 components travel through different paths in the receiver front end. Also shown in Figure 4 is the fact that the L_1 and L_2 delays tend to increase at the end of the day, although the temperature is stable at this time. This indicates that other causes may affect the delays. At the time of the writing, more experiments are conducted to find out the origin of this variation.

ON-SITE BASELINE EXPERIMENT

The synchronization errors obtained from the analysis of the code and phase observations over the 95-m baseline with common time reference are shown in Figure 5. As was the case for the zero baseline, the use of the carrier phase observations (Fig. 5.b) rather than codes (Fig. 5.a) shows a clear improvement (note that the larger noise on the carrier phases with respect to the zero-baseline test is due to multipath). Nevertheless, as seen from the frequency stabilities, the carrier phases and code analyses have similar efficiencies at the averaging time of one day. This is due to the long period fluctuations of the signal, which are perfectly correlated with the temperature variations nearby the receiver BRUE (Fig. 5.c). This large temperature effect (about 0.15 ns/°C) is partly due to the receiver BRUE and partly due to the cable driving the H-maser frequency to the receiver (about 90 meter in open air). The results in Figure 5 show that

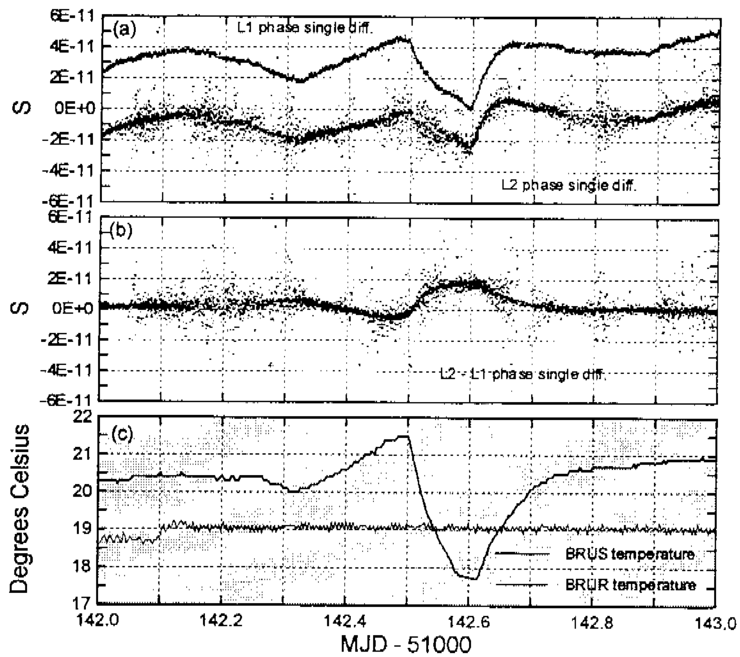

Figure 4: L_1-L_2 differential response to receiver temperature variations, deduced from the frequency transfer for a zero-baseline experiment where both receivers are driven by a same H-maser clock frequency, but one receiver (BRUR) is located in an air-conditioned room.

a frequency stability of a few parts in 10^{16} for averaging times of one day can be reached if all the instruments are located in temperature-stabilized rooms.

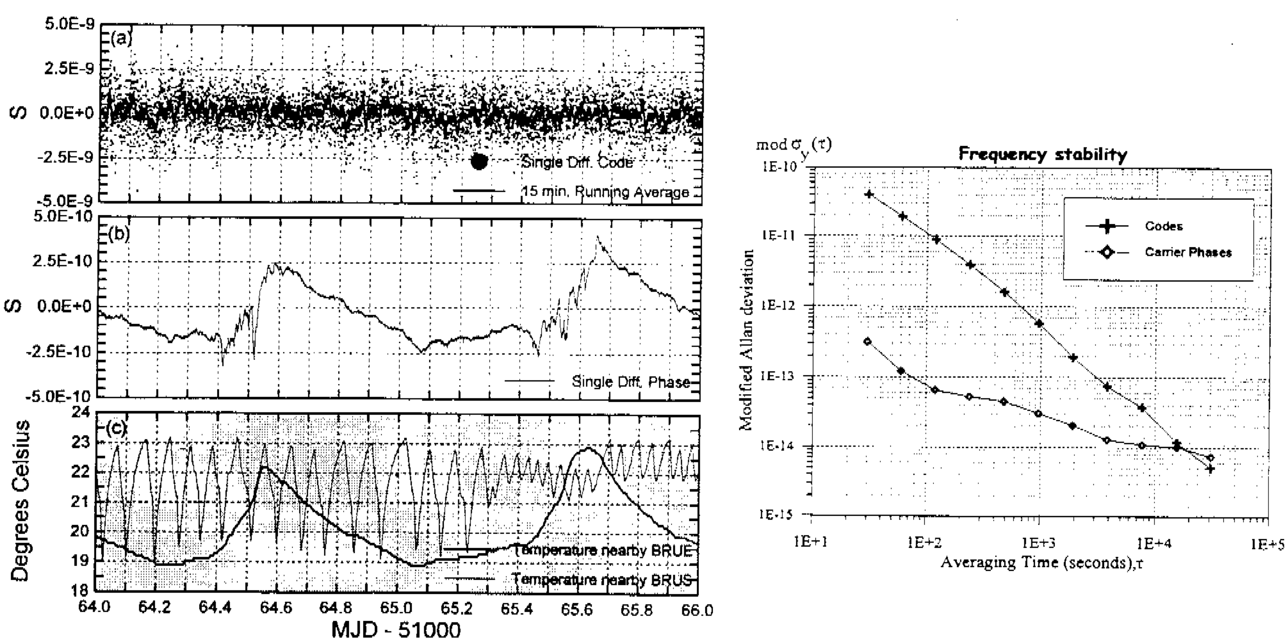

Figure 5: Time differences (H-Maser - H-Maser) and frequency stability analysis for a 95-meter-baseline experiment where both receivers are driven by the same H-maser clock frequency.

MEDIUM-LENGTH-BASELINE EXPERIMENT

Using Code Measurements

The stability of the frequency transfer between two remote H-maser clocks has was investigated on the 640-km baseline Brussels-Wettzell. Figure 6 compares the frequency stabilities obtained with the classic common-view method (C/A-code on one channel) and with several multi-channel code processing schemes: using broadcast or precise (IGS) ephemerides, and using C/A-code or the ionospheric-free P_3-code.

We can see that all multi-channel results provide the same frequency stability. From this, we can conclude that the IGS precise orbits do not improve the frequency transfer compared to broadcast ephemerides, and that the ionospheric-free P_3 code does not improve the frequency transfer compared to the C/A-code. The optimal method would be to use the C/A-code with an ionospheric model. Figure 6 also compares the "multi-channel" frequency stabilities with the classical common view; the improvement is clear.

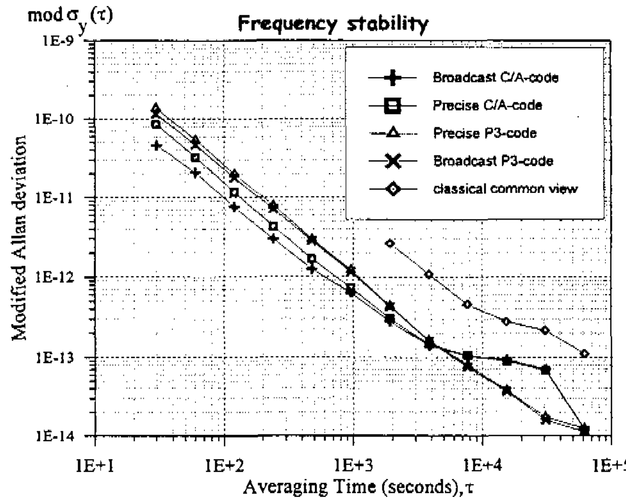

Figure 6: Frequency stability of the frequency transfer using different code data for the medium-length (640 km) baseline experiment where both receivers are driven by H-maser clock frequency.

Using Carrier Phase Measurements

The frequency transfer performed with codes can also be compared with the frequency transfer analysis performed with carrier phases. This is shown in Figure 7; the use of carrier phases shows a clear improvement.

Moreover, the analysis of phases allows again to identify some temperature effects in the frequency transfer, which are perfectly correlated with the temperature variations in the laboratory of BRUS. The amplitude of the effect is quite larger than what was deduced from the zero-baseline experiments, it reaches here about 0.5 ns/°C. Furthermore, from the study of the L_1-L_2 differential response of the receiver BRUS (see Figure 4), it appears clearly that the sensitivity of BRUS to temperature variations was only of about 10 ps/°K. We, thus, attribute the correlation of the temporal

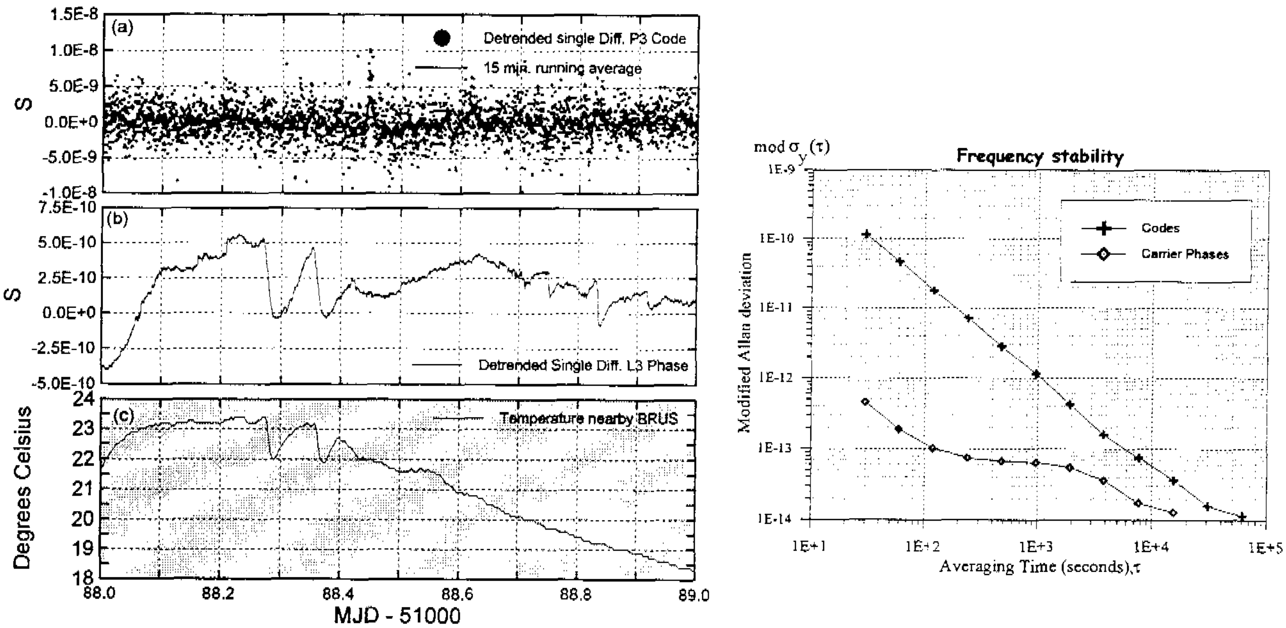

Figure 7: Time differences (H-maser BRUSSEL - H-Maser WETTZELL) and frequency stability analysis for a medium-length (640 km) baseline experiment.

variations with the computed synchronization errors to the amplifier of the H-Maser frequency, which is located in the same laboratory as BRUS and subject to identical temperature conditions.
This has also been confirmed by the direct comparison of the 1pps signal from the H-Maser clock with the 1pps signal output from the receiver BRUR when this one was in an air-conditioned room. From this, we can conclude that the frequency stability of the frequency transfer with carrier phase is limited, due to the influence of temperature variations on the amplifier (not in an air-conditioned room) of the H-maser frequency.

CONCLUSION

We have tested the stabilities of frequency transfer over three types of baselines : a zero, short and medium-length. The computations were done independently on using first the GPS code observables and later the carrier phases. We have demonstrated that in the present situation (where the instruments are not in temperature-stabilized laboratories), the frequency stability for averaging times of one day are 6×10^{-16} for the zero baseline, 6×10^{-15} for the on-site tests with a 95 m baseline between both antennae, and 10^{-14} for a medium-length baseline between Brussel and Wettzell (640 km).The main limitations of our analyses are presently the response of the different hardware components to ambient temperature changes. For some of the components we have derived temperature coefficients : the responses of the receivers is of about 30 ps/°C (depending on the receiver type), the response of the amplifier of the H-Maser frequency is of about 0.5 ns/°C.
The frequency stabilities obtained here can be largely improved if the temperature effects on the instruments are suppressed, i.e. if the instruments are all located in temperature-stabilized rooms. In that case, the frequency transfer using carrier phases for longer baselines should gain more and more interest, and the combined use of code observations could allow to estimate the "absolute" time offset between the receiver internal clocks, and hence between the local clocks connected to the receivers.

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