"COMMON VIEW" CLOCK SYNCHRONIZATION OF REMOTE ATOMIC CLOCKS USING GPS AND PRARE ONBOARD ERS-2

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SUMMARY

The paper presents a validation test for two-way clock comparison with the help of the PRARE instrument onboard ERS-2 and with two of the PRARE system stations, which are provided with atomic clocks. A "Common View" ground-clock synchronization scenario has been performed, using the PRARE instrument and GPS time receivers connected to an atomic clock at each ground station site. By computing and comparing the results respectively the accuracy for the PRARE instrument has been estimated. The achievable synchronization accuracy for the PRARE equipment in this "Common View" mode is around 1 ns, due to the sub-optimum design of the existing PRARE system for time purposes. The experiment turns out that the PRARE system combined with a highly stable frequency source onboard a suitable satellite is qualified to be a basic element for a future GNSS II.

1. INTRODUCTION

When investigating navigation systems of the next generation new methods for synchronization of the ground and satellite clocks (S/C's and G/C's) have to be discussed. Besides the conservative one-way method with its known drawbacks in combining clock and ephemeris errors, two-way methods seem to be important concerning better synchronization accuracy. In Bedrich (1) a precise two-way microwave time transfer link has been described. It has been shown that the existing PRARE system can be modified for such purposes. The PRARETIME instrument has been introduced. A detailed study can be found in Hahn (2).

To test the described in these papers two-way clock comparison method, an experiment has been planned between DLR and GFZ in 1995 performing a "Common View" (CV) G/C synchronization scenario by means of PRARE onboard ERS-2 and GPS time receivers. For DLR it was the first experiment with PRARE equipment data. The main goal of this experiment was clock comparison via two-way microwave time links. Existing systems like MITREX use geostationary satellites (GEO) for this purpose. But a GEO only covers a certain area of the Earth. For global time comparison operation or time dissemination a polar orbiting reference has to be used. Two-way clock synchronization using an orbiting time reference has been studied.

2. MEASUREMENT PRINCIPLE

During the measurement campaign two different clock comparison techniques have been used simultaneously: clock comparison via

- GPS CV and
- PRARE instrument onboard ERS-2.

These methods are outlined below.

2.1 GPS-"Common View"

The GPS CV is a well proved time comparison method of remote clocks using the BIPM GPS tracking schedule (presently schedule no 26). Following this schedule, all participating time receivers monitor a dedicated GPS satellite clock simultaneously.

Each GPS time receiver with its reference clock REF_i records the time difference $(REF_i\text{-}SV_j)_m$ averaged over a certain interval (780 sec) at time t_m, where j is the pseudo range number of GPS satellite SV. Data correction accounting for ionospheric, tropospheric, relativistic and range delays are implemented in the receiver with different effort.

By exchange and substracting the recorded files the clocks REF_i and REF_k can be synchronized respectively and the clock offset D_{ik}^{GPS-CV} at time t_m is

$$\begin{aligned} D_{ik}^{GPS-CV}(t_m) &= (REF_i - SV_j)_m - \\ &\quad -(REF_k - SV_j)_m \qquad (1) \\ &= (REF_i - REF_k)_m . \end{aligned}$$

Repeating this procedure for any available time t_m, t_{m+1}, t_{m+2}, ... the rate R between the clocks can be computed over a certain time interval. The accuracy for this comparison method is around 3.6 ns following Lewandowski (3).

2.2 PRARE Clock Comparison

The PRARE instrument operates in two-way mode (signal flow: space-ground-space). This allows to measure the clock offset $D_{Sk}^{TW}(t_m)$ of the involved S/C REF_S and G/C REF_k, if the asymmetry $\Delta\tau_{Sk}(t_m)$ of the two paths is determined. This is fulfilled by measuring the signal travel time at the S/C, round-trip travel time $\Delta d_{2k}(t_m)$, and additionally (simultaneously) at the G/C site, one-way travel time $\Delta d_{1k}(t_m)$ (cf. fig. 1).

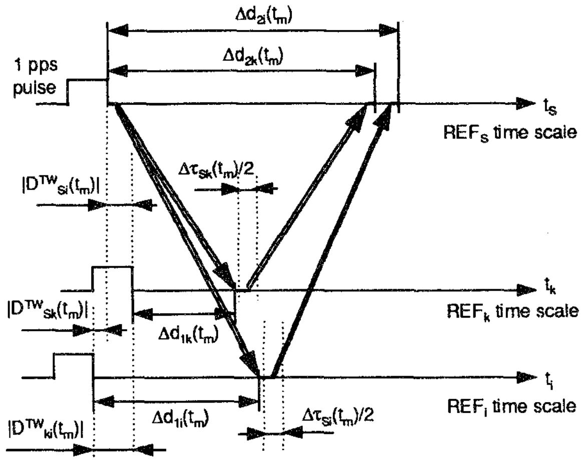

Fig. 1 Principle of two-way clock comparison (CV mode)

The clock offset can be determined with

$$D_{Sk}^{TW}(t_m) = \Delta d_{1k}(t_m) - \frac{\Delta d_{2k}(t_m) + \Delta\tau_{sk}(t_m)}{2}. \qquad (2)$$

The microwave signal transmitting the frequency and time information is subject to diverse disturbances on its way from clock to clock causing asymmetries ($\Delta\tau_{Sk}$) between the signal paths.

One can distinguish between internal, i.e. hardware and measurement errors on both sides, and methodic, i.e. signal transmission and correlation errors. The residual accuracies of models or supplementary measurements which correct those deviations define the achievable clock synchronization accuracy.

While the microwave signal travels the ionosphere with frequency f_X, a coherent signal on a second frequency f_S with correlated reception gives the possibility to correct very precisely for ionospheric delays (different down- and uplink frequencies in X-band). If $\Delta d_{1k}^X(t_m)$ and $\Delta d_{1k}^S(t_m)$ indicate the one-way travel times in X- and S-band (f_X and f_S) respectively, the ionospheric delay time $\Delta\tau_{IX}(t_m)$ for the X-band signal will be equal to

$$\tau_{IX}(t_m) = \frac{\Delta d_{1k}^X(t_m) - \Delta d_{1k}^S(t_m)}{f_X\left(\frac{1}{f_X^2} - \frac{1}{f_S^2}\right)}. \qquad (3)$$

Tropospheric corrections have to be included by meteorological measurements and appropriate modelling; all other influences depend on the calibration efforts.

The simultaneous PRARE Doppler measurements f_{D2} (two-way in PRARE) have to be included to solve for the range asymmetry $\Delta\tau_d$

$$\Delta\tau_d = \frac{\Delta d_{2k}}{2} \cdot \frac{f_{D2}}{f_{Down}}, \qquad (4)$$

with f_{Down} being the downlink frequency.

Relativistic effects have to be considered for utmost accuracy requirements.

In the neighborhood of culmination point at time t_{cul} the asymmetry $\Delta\tau_{Sk}(t_m)$ reaches its minimum due to almost reciprocal signal paths. This time moment has to be preferred for data processing.

Exchange of the measurement results between the clocks has to be done by data transfer (for example in the message frame of the PRARE microwave links). The main advantage of two-way measurements is the fact that slant range r and clock offset $D_{Sk}^{TW}(t_m)$ are achievable one without the other, i.e. the clock offset $D_{Sk}^{TW}(t_m)$ is obtained without knowledge of the clocks' distance, and the slant range r is obtainable without information about the clocks' deviation. On the other hand for picosecond level of accuracy relativistic effects have to be calculated using precise orbit information.

Synchronization of remote G/C's mutually is possible by CV observation of the S/C. Fig. 1 gives a scheme for comparison of clocks REF_i and REF_k.

When substracting the computed clock offsets $D_{Sk}^{TW}(t_m)$ and $D_{Si}^{TW}(t_m)$, the clock offset $D_{ki}^{TW}(t_m)$ between the ground clocks can be calculated.

3. EXPERIMENTAL SETUP

Fig. 2 presents an overview of the experimental setup with ground station sites in DLR's branch in Lichtenau near Weilheim and GFZ's branch in Oberpfaffenhofen near Munich. Each station was equipped with an appropriate PRARE station and GPS time receiver and are described in section 4.

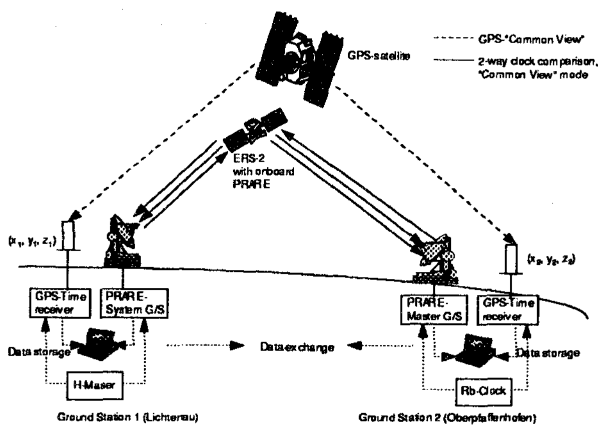

Fig. 2 Scheme of experimental setup

4. HARDWARE CALIBRATION

The always critical matter is careful calibration of instrumental hardware. Only by this way utmost accuracy can be reached.

The PRARE instrument performes the calibration by itself (calibration loops, etc.). Corresponding figures are available in the recorded data files. The additional one-way measurement must be calibrated by the experimenter. This concerns essentially cable delays between clock, PRARE processor and time interval counter (TIC), and electronic switches, plugs, isolation amps.

In the GPS time receiver, common receiver, antenna, and clock cable delays must be accounted for. These delays are considered in the data processing. During a 7 weeks measurement campaign in 1990 a comparison between the two involved GPS time receivers had been performed. Here both receivers had been operated at the same location with the same clock. A bias could be determined with an order of about 200 ns.

To overcome this problem in the present experiment, a new comparison was neccessary and initialized. A third GPS time receiver AO TTR5 was used, operating at each ground station site with the same ground clock respectively for a duration of one week. The bias between the ground station receiver and this third receiver has been evaluated. Finally the bias between the two ground receivers presently valid could be estimated with presently about 40 ns and considered in the data computation.

4.1 Ground station site in Lichtenau (station 1)

The principal structure of the experimental setup in DLR's branch in Lichtenau can be obtained from fig. 3.

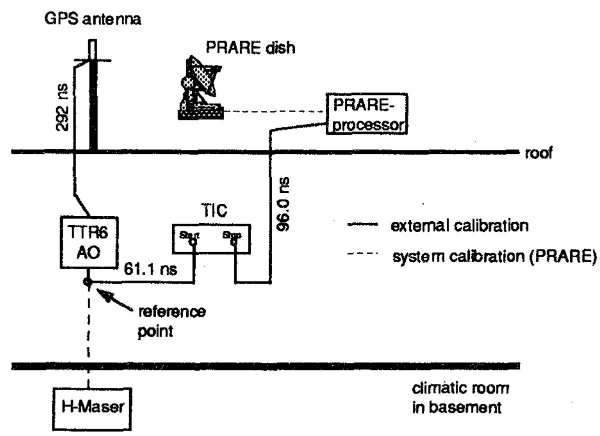

Fig. 3 Setup at DLR's ground station site

The reference clock, a H-maser CH1-75 of Russian company "KVARZ" is located in a climatic room in the basement. The GPS time receiver AO TTR6 operates in the time lab where the TIC for the one-way measurement is placed too. The PRARE processor with antenna dish at roof is connected via cable to the TIC in the time lab. The cable delays have been determined as shown in figure 4 and will be denoted as $\Delta\tau_{start1}$ = 61.1 ns, $\Delta\tau_{stop1}$ = 96 ns. The cable delay of 292 ns to the GPS antenna is considered in the TTR6 data processing.

4.2 Ground station site in Oberpfaffenhofen (station 2)

The setup in GFZ's branch in Oberpfaffenhofen which corresponds particulary to the PRARE Master Station configuration can be seen in fig. 4. The reference clock is represented by a Rb-clock in phase locked redundancy by EFRATOM which is DCF-77 disciplined to follow the UTC(PTB) time scale, cf. Bedrich (4). Also a GPS time receiver AO TTR6 with a TIC for registration of one-way measurements is located in the operation room. The PRARE processor with antenna dish at roof is connected via cable to the TIC in the operation room. The cable delays have been determined and can be obtained from fig. 4 respectively and will be denoted as $\Delta\tau_{start2}$ = 5 ns and $\Delta\tau_{stop2}$ = 209.5 ns. The cable delays of 298 ns and 5 ns to GPS antenna and clock reference point are considered in the TTR6 data processing.

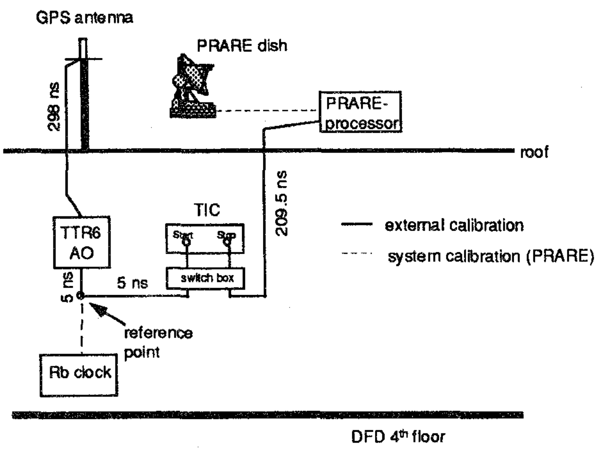

Fig. 4 Setup at GFZ's ground station site

5. DATA EVALUATION

All data have been recorded between December 1995 and February 1996. Below an example of the data analysis of GPS and PRARE observables is given.

5.1 GPS-CV

Fig. 5 presents the result of GPS clock comparison between the two clocks involved in Lichtenau (H-maser) and Oberpfaffenhofen (Rb) respectively over the whole observation duration.

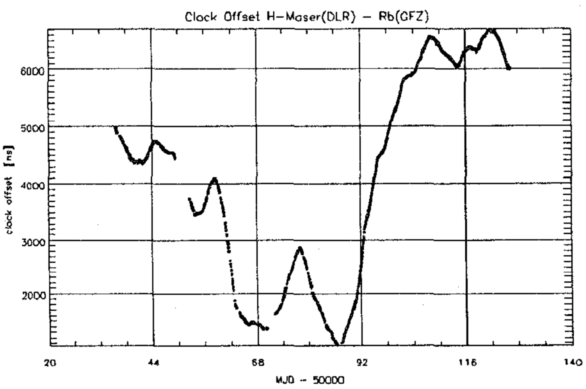

Fig. 5 Result of GPS CV between DLR's H-maser and GFZ's DCF77 disciplined Rb-clock

It has to be mentioned again that GFZ's rubidium clock is DCF77-disciplined to follow the UTC(PTB) time scale. That can be seen in fig. 5 - each third day a correction is applied, the rate is due to this Rb-clock. The observed offset of 40 ns between the two GPS time receivers has been considered.

5.2 PRARE data

For clock comparison, the following data were available from the PRARE instrument data processing (the station index will not be added for simplification),

in either range and Doppler measurement files:

- date and time of event, t_m;
- azimuth *az* and elevation *el* at ground station, [°];
- air pressure *pr*, [hPa], air temperature *T*, [K] and air humidity *hu*, [%] at ground station;
- tropospheric refraction correction (2-way) $\Delta\tau_{T2}, \Delta\tau_{TC2}$, [ps] or [cycles];
- ionospheric refraction correction (2-way) $\Delta\tau_{I2}, \Delta\tau_{IC2}$, [ps] or [cycles];
- satellite centre of mass correction (2-way) $\Delta\tau_{M2}, \Delta\tau_{MC2}$, [ps] or [cycles];
- onboard PRARE antenna phase centre correction (2-way) $\Delta\tau_{P2}, \Delta\tau_{PC2}$,[ps] or [cycles];
- ground station mechanical centre correction (2-way) $\Delta\tau_{C2}, \Delta\tau_{CC2}$, [ps] or [cycles];
- external calibration correction (2-way) $\Delta\tau_{E2}, \Delta\tau_{EC2}$, [ps] or [cycles];
- X-band versus S-band travel delay measurement (1-way, space to ground) $\Delta\tau_{XS}$, [ps];

in only range measurement files:

- two-way travel time (each second) including internal calibration of the space segment and ground station and 91 value range correction Δd_2, [ps];

and in only Doppler measurement files:

- measured Doppler cycles (2-way) including internal calibration of the space segment and ground station Δd_{C2}, [cycles];
- frequency offset relative to nominal satellite frequency 8.489 GHz $\Delta\tau_{OF}$.

One-way travel time measurements Δd_1 were recorded at each ground station site with date and time of event t_m and figures in [ps].

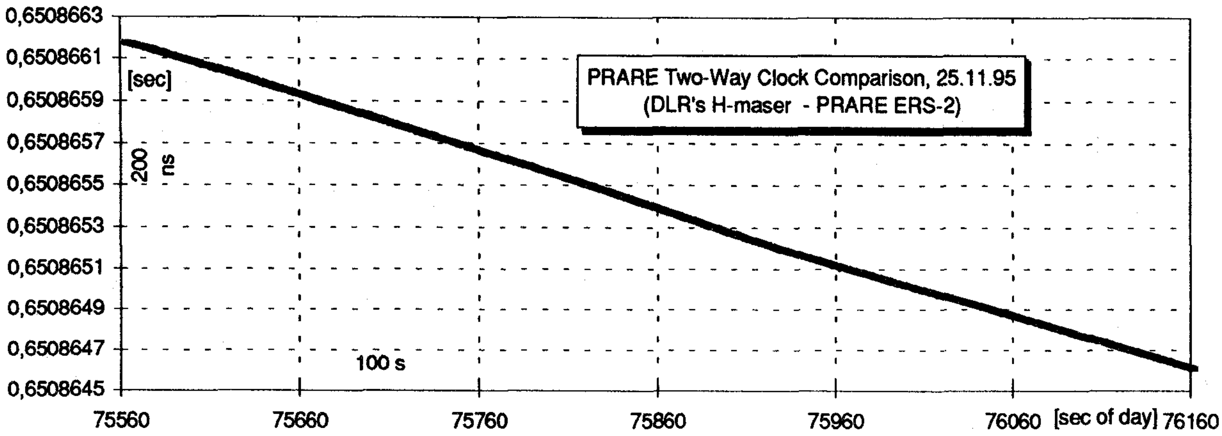

Fig. 6 Example of two-way clock comparison between DLR's H-maser and PRARE onboard clock

Generally the time offset has been determined following equation (2). The data designated at

$t_m, \Delta\tau_{I2}, \Delta\tau_{IC2}, \Delta\tau_{P2}, \Delta\tau_{PC2}, \Delta d_1, \Delta\tau_{E2}, \Delta\tau_{EC2}, \Delta\tau_{XS}, \Delta d_2, \Delta d_{C2}$, and $\Delta\tau_{OF}$

have been applied in the present work to compute the time offset and account for asymmetries on the propagation path.

The two-way range measurement Δd_2 has been corrected to Δd_{2c} following instructions from the PRARE processing team to be

$$\Delta d_{2c} = \Delta d_2 - \Delta\tau_{I2} + \Delta\tau_{P2} + \Delta\tau_{E2} + \Delta\tau_d, \qquad (5)$$

where $\Delta\tau_d$ being the correction for range asymmetries due to different up- and downlink paths and calculated as

$$\Delta\tau'_d = \Delta d_{C2} + \Delta\tau_{IC2} + \Delta\tau_{PC2} + +\Delta\tau_{EC2} + \Delta\tau_{OF}, \qquad (6)$$

$\Delta\tau_d : \Delta\tau'_d \longrightarrow eq.(4).$

The one-way signal travel time Δd_1 was corrected to Δd_{1c} using

$$\Delta d_{1c} = \Delta d_1 - \Delta\tau_{IX} + \Delta\tau_{start} - \Delta\tau_{stop}, \qquad (7)$$

$\Delta\tau_{IX}[ps] : \Delta\tau_{XS} \longrightarrow eq.(3).$

Finally the time offset between satellite S and ground station k was evaluated with

$$D^{TW}_{Sk}(t_m) = \Delta d_{1ck} - \frac{\Delta d_{2ck}}{2}, \qquad (8)$$

(here the station index is added).

An example of two-way clock comparison between the H-maser reference in Lichtenau and PRARE onboard clock (ERS-2) during a 600 sec pass on 25 November 1995 presents fig. 6. Here the rate of the PRARE oscillator can be identified; it includes relativistic effects which have not been accounted for yet.

6. DISCUSSION OF RESULTS

In the following, the results of the differential data processing of the PRARE pass from 25 November 1995 (cf. fig. 7) are presented.

The pass had a duration of about 650 sec. Data points calculated are smoothed over 30 sec. The standard deviation from the linear regression line is given by a figure of 770 ps (1σ). To compare the processed time offset with the GPS CV results, the midpoint of the regression line has been determined to be

D^{TW}_{12} (t_m = 75878 sec of 25 Nov 1995) =
= 4485.66 ns.

For the time corresponding to the above evaluated midpoint GPS CV clock data have been processed in the following manner: For the 25 November 1995 a linear regression line has been computed. The clock offset corresponding to the midpoint of PRARE pass has been evaluated by interpolation to be

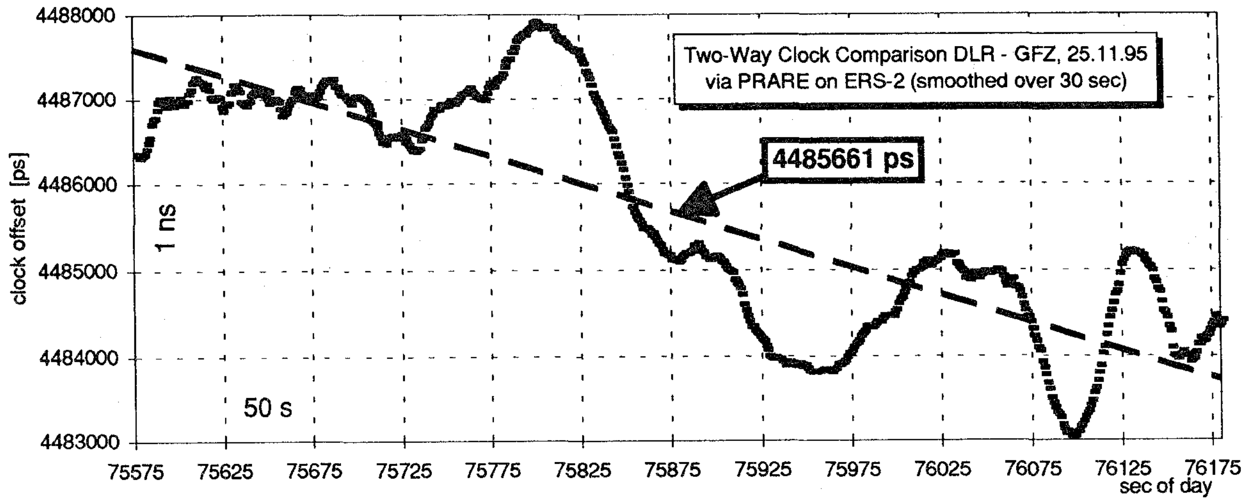

Fig.7 Result of PRARE clock comparison, DLR's H-maser - GFZ's Rb, 25.11.95

D_{12}^{GPS-CV} (t_m = 75878 sec of 25 Nov 1995) =
= 4550.63 ns.

Here the standard deviation from the linear regression line is given by a figure of 8.91 ns (1σ).

With a great number of other PRARE CV data processings the fact could be verified that the precision of PRARE two-way clock comparison in present design is always around 1 ns.

Concerning accuracy, a bias discrepancy of 65 ns to GPS CV computation was computed. The reasons are:

- uncertainty of time offset between the GPS time receivers;
- the calibration measurement was not sufficient for accurate GPS calibration;
- missing one-way travel time calibration of the PRARE ground stations.

7. CONCLUSION

Differential two-way clock comparison (ground to ground) by means of PRARE onboard ERS-2 is presently possible with a precision of around 1 ns. A similiar figure is expected for space to ground clock comparison causing from the two-way principle. The achievable accuracy which is supposed to be of the same order must be further investigated. Due to time constraints this matter could not discussed finally (calibration problems with GPS).

The experiment emphasizes the possibility of highly accurate global clock comparison and time transfer if a two-way time and ranging system of PRARE like type is carried onboard a polar orbiting satellite. The results point out that in conjunction with an ultrastable onboard reference this configuration could be applied for clock synchronization within future satellite navigation systems (GNSS I and II) and for benefit of the whole time community.

ACKNOWLEDGEMENT

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