Two-way satellite time transfer for Galileo

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INTRODUCTION

Two-way satellite time and frequency transfer (TWSTFT) using geo-stationary telecommunication satellites has proven as the most appropriate means of comparing time scales and atomic frequency standards with an uncertainty in time of less than 1 ns and with relative uncertainty for frequency of about 1 part in 10^{15} at averaging times of one day. This is why TWSTFT is widely used in the international network of time keeping institutions supporting the realization of International Atomic Time (TAI) [1]. For the very reasons, TWSTFT has been chosen as the primary means to synchronize the two Precise Timing Facilities (PTF), part of the Ground Mission Segment of the European satellite navigation system Galileo, as well as to support the measurement of the time difference between GPS time and the Galileo System Time (GST) [2]. Requirements were developed according to which TWSTFT shall enable time scale comparisons with a measurement precision of less than 1 ns for a measurement duration of 2 minutes and an accuracy of 1 ns over an extended period. In this contribution we discuss to which extent these requirements can probably be fulfilled under the current operational practices. The latter stem from the fact that during the so-called Galileo In-Orbit-Validation phase, scheduled for 2008/2009, the PTFs shall become part of the existing European TWSTFT network which currently consists of 12 timing institutes.

After a very brief repetition of the theoretical background of TWSTFT, we report on studies regarding the increase of measurement noise with an increasing number of stations, and regarding the tolerable range of the stations' transmission power. Here we concentrate on the performance as relevant for Galileo operations whereas in [3] we had a broader view, including frequency transfer between primary frequency standards. To ensure the time transfer accuracy, periodic calibration of the time links is required, and we discuss the strategy followed for IOV to ensure the accuracy requirement referring to a recent campaign [4].

BACKGROUND

Currently TWSTFT is made using fixed satellite services in the Ku-band and the X-band. It is done by transmission of pseudorandom noise (PRN) binary phase-shift keying (BPSK) modulated carriers. The phase modulation is synchronized with the local clock's one pulse per second (1pps) output. Each station uses a dedicated PRN for its BPSK sequence in the transmitted signal. The receive equipment allows to generate the BPSK sequence of the remote stations and to reconstitute a 1pps tick from the received signal. This is measured by a time-interval counter (TIC) with respect to the local clock. Following a pre-arranged schedule both stations of a pair lock on the code of the corresponding remote station for a specified period, measure the signal's time of arrival, and store the results. After exchanging the data records the difference between the two clocks is computed. Details of the data reduction and the systematic effects involved are discussed in [5].

Operational parameters, such as transmission power, receiver carrier-to-noise density ratio (C/N_0), BPSK chip rates, as well as the installed hardware have an impact on the noise in a TWSTFT measurement setup. The measurement noise can be characterized by analyzing the 1pps output of the modem. It reflects the time of arrival of the time signal transmitted from a remote modem in a regular TWSTFT session or from the same modem in the case of satellite ranging (measurement of the round-trip signal propagation to the satellite and back). The modems for modulating and demodulating the signals in the 70 MHz intermediate frequency band are based on technology originally developed by Hartl et al. [6] (MITREX modem). In [6] a functional description of the expected 1pps jitter when working with a signal of a given C/N_0 and BPSK chip rate is given. The SATRE modem which is widely used today includes improved signal processing technology and provides a reduced 1pps jitter as shown in Fig. 1 in which the expected 1pps jitter values for the current standard value of 2.5 MCh/s and some lower and higher chip rates are given. For the current standard C/N_0 value of 55 dBHz the 1pps jitter, when receiving a 2.5 MCh/s signal, is predicted as low as 500 ps [7], significantly less than stated in [6].

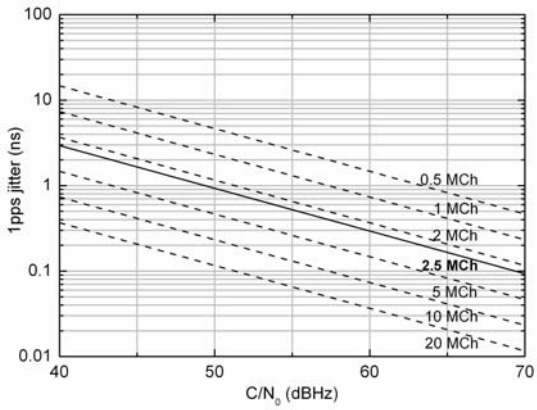

Fig. 1. SATRE modem measurement noise (1pps jitter, DRMS) as a function of C/N_0 after Hartl et al. [6] and Schäfer [7] for different chip rates (0.5 MCh/s to 20 MCh/s).

When speaking of the 1pps jitter in this work we mean the rms of the residuals to a quadratic fit to the TIC measurements, typically taken during sessions of 120 s duration. Following the ITU-R Recommendation TF.1153-2 [8] we designate this quantity as DRMS throughout this paper. The DRMS in Fig. 1 is typically very close to the time deviation $\sigma_x(\tau=120\text{ s})$ since the prevailing noise type leads to a constant $\sigma_x(\tau)$ up to longer averaging times – up to several 1000 s - when clock noise starts to dominate. Actually $\sigma_x(\tau=120\text{ s})$ is the quantity which has to be compared with the above mentioned requirement.

OUTLINE OF THE CURRENT EXPERIMENTS

All experiments reported further on were made using transponder 77/371 on the satellite INTELSAT-707 at 307°East. The measurement schedule and code assignment was agreed by the CCTF Working Group on TWSTFT. Nominally 12 European stations operate in a sequence during “even” hours 00:00 to 00:59, 02:00 to 02:59, and so on, of a day. During the odd hours usually no TWSTFT experiments are scheduled. These hours are reserved for experimental studies such as the ones reported here but also for the operation of delay monitoring equipment. Each of the regular sessions starts with transmitting an unmodulated (“clean”) carrier with a transmission frequency individually assigned to stations. Then a ranging measurement is made during which each station receives its own signal, and then the scheduled comparisons start. Transmission of a clean carrier signal allows to identify stations on-line and to monitor the power with which they transmit.

The measurement noise has been investigated using three different experimental setups:

1) Ranging measurements using the PTB’s ground station (modem SATRE S/N S280)
2) Two modems (S280 and S037) connected to PTB’s ground station with a frequency divider/combiner device inserted in the IF path to enable parallel operation of both modems. Thus both modems are operated in a common clock TWSTFT mode, they share, however, one set of converters, amplifiers and one antenna.
3) TWSTFT between the stations at METAS and PTB (acronyms CH and PTB, respectively).

EXPERIMENTAL RESULTS

Noise during regular TWSTFT sessions

The European TWSTFT network comprises 12 laboratories as shown in Fig. 2. In this configuration 6 pairs of laboratories can compare their time scales simultaneously. This means, that one station locks on the code of one remote station while in the "worst case" simultaneously 11 other signals transmitted through the satellite transponder are received as well and contribute to the noise in the received signal and thus decrease the C/N_0 value.

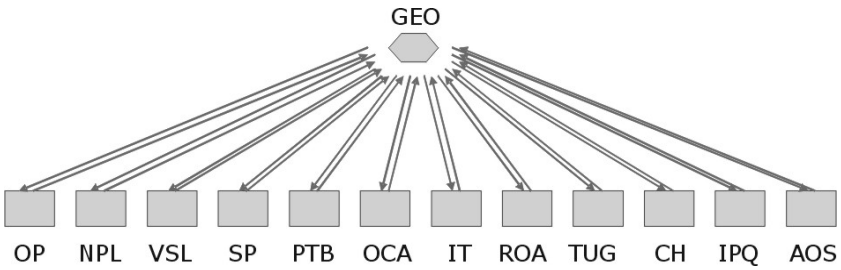

Fig. 2. The European stations of the US/European TWSTFT network. U.S. laboratories are NIST an USNO, but not further mentioned here since reception of signals from the U.S requires another receive frequency. CH is the TWSTFT station acronym for METAS and used here and in the text.

At first we study the 1pps jitter observed during ranging measurements at PTB. As depicted in Fig. 3, from MJD 53800 to MJD 53950 ranging measurements were scheduled during both the even as well as during the odd hours. While in the even hours at most 12 stations were transmitting, "on air", during the odd hours only two stations were on air, i.e. the PTB and the CH station. The reduction of the DRMS when using a "quiet" transponder channel is evident. While the DRMS average for the even hours is 0.73 ns the value obtained during odd hour is 0.53 ns on average, representing an improvement by a factor of 1.4.

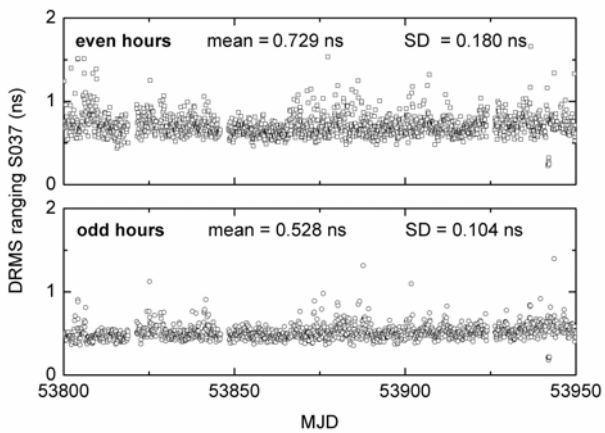

Fig. 3. DRMS values of ranging measurements at PTB (S037) during the period MJD 53800 to MJD 53950 sorted for even (11 stations on air) and odd (2 stations on air) hour measurements

Similar results are obtained in common clock measurements and for TWSTFT measurements with METAS (see Table 1). Receive parameters were recorded for the common clock experiments. While the receive power level during even and odd hours was at the same level, the C/N_0 values were slightly higher during the odd hours, explaining the smaller DRMS values determined at the same time.

Table 1. Summary of the DRMS values (in ns) from measurements during even and odd hours. Note that due to the schedule not all stations are transmitting during the two minutes of the CH-PTB comparisons.

	Hour	Ranging	Common Clock	TWSTFT CH-PTB
Stations on air	even	11	11	6
	odd	2	2	2
DRMS (ns)	even	0.73	0.44	0.58
	odd	0.53	0.31	0.45
Ratio		1.4	1.4	1.3

The last column in Table 1 refers to the comparison of two hydrogen masers at METAS and PTB during the period MJD 53900 and MJD 53970 (see Fig. 4). The frequency transfer capability over extended periods could not be assessed due to the rather large frequency instability of the masers involved. A clear improvement e. g. for the one-day frequency averages obtained from data taken in even and odd hours, respectively, was not achieved. A more rigorous study would require the availability of two independent frequency transfer techniques by which the clock noise could be eliminated as was demonstrated earlier in [9] and more recently in [10].

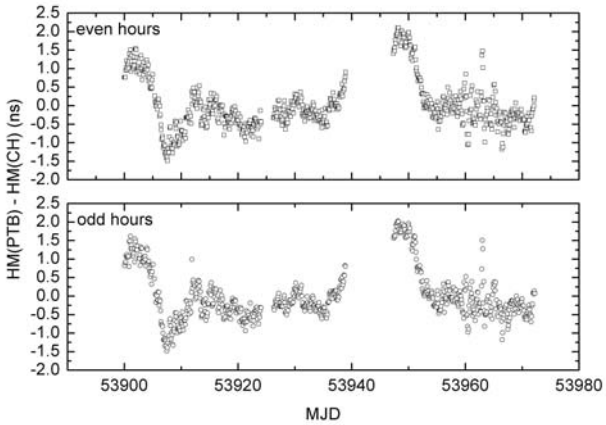

Fig. 4. H-maser comparison between CH and PTB (S037) via regular TWSTFT. A second order polynomial is subtracted from the raw data.

TWSTFT measurement noise as a function of the receive power

In a network which is operated on a routine base, each participating station is in principle obliged to keep its operational parameters constant. Only the assigned codes should be used and the transmission (Tx) power level should be kept constant at a pre-arranged level since the Tx level of the transmitting station dictates the C/N_0 value obtained at a remote station receiving this signal. In Fig. 5 the C/N_0 of ranging measurements as a function of Rx-power are depicted. The data scatter around a line with slope 1.

It was tested in the common clock configuration, if an increase of the Tx-power provided by modem S280 has a significant impact on the noise level of the signal received with S280 coming from modem S037 which provided constant transmission power of –17 dBm and on the noise level of the signal received with modem S037. In Fig. 6 the DRMS values for both received signals are displayed. As expected, the S037 DRMS values (full symbols) decrease strongly with increasing the Tx power of S280, since modem S037 gets a more and more strong signal to lock on. On the other hand, the DRMS values obtained from the Rx channel of S280 (open symbols) remain essentially constant except for the point taken at the highest S280 power. We notice from the points at the same signal power of –17 dBm that the receive channel of the new modem S280 is less noisy than that of the old modem S037.

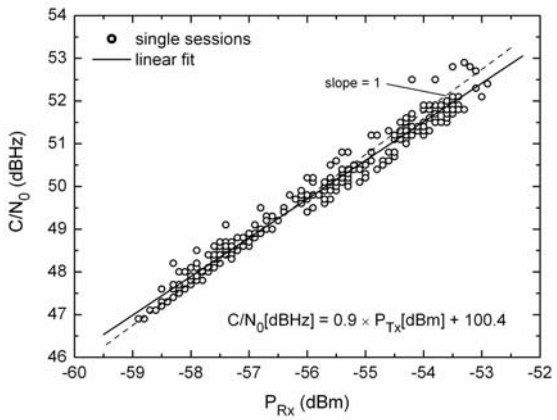

Fig. 5. C/N_0 as a function of Rx power during ranging measurements with modem S280.

An evaluation of the time transfer results for this common clock configuration reveals a strong dependency of the time transfer result on the Tx power provided by S280 as shown in Fig. 7. While at moderate Tx-powers from –21 dBm to –15 dBm only a small impact of 40 ps/dB can be estimated, at higher Tx-powers the time transfer results strongly depend on the Tx-power. We are currently discussing these findings with the modem manufacturer but cannot provide a conclusive explanation here. Typical PTB modem operation power in the TWSTFT network is at –17 dBm, but even at such low values the Tx power should be controlled within +/ 1 dB to ensure that any variation of time transfer results is well below 0.1 ns.

We have to concede that the common clock experiment is carried out with only one TWSTFT ground station, as described above. The strong sensitivity of the time transfer results might be a measurement artefact caused by not identified interferences in that special measurement configuration. However, it was reported before that strong disturbing signal (even if they use different PRN codes) can introduce interferences in time transfer measurements [11]. We plan to repeat similar tests during extra TWSTFT measurements with a remote station.

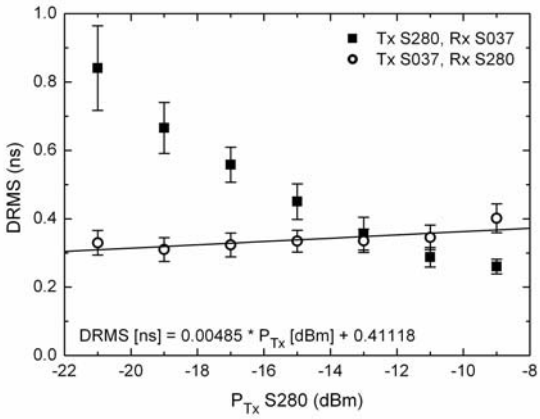

Fig. 6. DRMS values for common clock TWSTFT measurements as a function of the variation of the Tx power of one modem (S280), while the modem S037 provided the same Tx power level throughout the experiments.

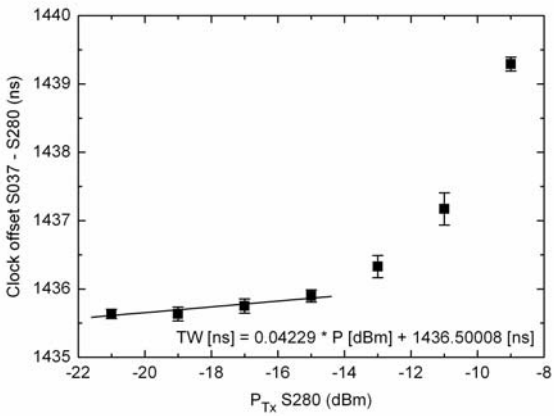

Fig. 7. Common clock time comparison results when varying the transmission power in one of the modems (S280). The constant offset from zero is due to missing calibration of the S280 delays when taking these data.

In conclusion, considering the performance of currently produced modems and being confident that technical installations and operations will follow accepted standards, the TWSTFT measurement precision will be compliant with the above Galileo requirements, even in a network of 14 stations.

TWSTFT Calibrations

In order to perform true time comparisons it is necessary to determine the differential signal delays in the stations involved. This is possible in different ways. The method to be applied during Galileo IOV is following the practice developed in recent years in Europe. A portable earth station will be co-located with the ground stations involved in the link. The most recent campaign of this kind was performed between Technical University of Graz, Austria, (TUG) METAS and PTB. We briefly recall the theoretical basis of such a calibration. Details on the implementation of this and previous campaigns can be found in [4, 12]. To develop the basic equations for a calibration of a TWSTFT-link we start from the general equation for a time transfer as given in [8]. Equation 1 gives the time scale difference measured with two TWSTFT stations when individual measurements are reported and the corrections for the Sagnac effect, propagation delay through the ionosphere and satellite delay differences are considered individually.

$$\begin{aligned} \mathrm{UTC}(k) - \mathrm{UTC}(l) = {} & +0.5\,(\mathrm{TI}(k) + \mathrm{ESDVAR}(k)) + \mathrm{REFDLY}(k) \\ & -0.5\,(\mathrm{TI}(l) + \mathrm{ESDVAR}(l)) - \mathrm{REFDLY}(l) \\ & +0.5\,C_{\mathrm{Sagnac}}(k, l) + 0.5\,C_{\mathrm{iono}}(k, l) + 0.5\,\mathrm{CALR}(k) - 0.5\,\mathrm{CALR}(l) + 0.5\,\mathrm{XPNDR}. \end{aligned} \tag{1}$$

Clearly if the two PTFs would be involved, the left hand side would read GST(1)-GST(2) where GST(i) would represent the two realizations of GST. In (1) TI(i) is the measured time interval at station i, ESDVAR(i) is the known change of the earth station delay difference since a previous calibration, REFDLY(i) is the delay between the SATRE modem time reference and UTC(i), $C_{\mathrm{Sagnac}}(k, l)$ is the Sagnac correction for a link between site k and site l, C_{iono} is the correction of the difference of the ionospheric delay, CALR(i) is the difference between transmit and receive path of station i, XPNDR is the correction for the transponder delay difference of the satellite.

A calibration with a portable earth station (PES) requires two steps. First, the PES is co-located with one of the fixed ground stations of the link to be calibrated (site 1). A common clock experiment is carried out, i. e. both the fixed and the portable TWSTFT station are connected to the same clock. In a second step, the PES is transported to the other fixed ground station (site 2) where the same procedure is repeated. In the following, we shall refer to the three TWSTFT-stations involved as 1, 2 and PES, respectively. For each site, the time transfer experiment between the PES and the fixed earth station is described by the general equation 1. However, due to the co-location and to the common clock, several terms drop out. The timescale difference is zero and the Sagnac effect and the difference of the ionospheric correction can be neglected. Also, by definition, the variable ESDVAR(i) is set to zero, as it is meant to take into account any variation of the earth station delay since a previous calibration. Finally, the same transponder on the satellite is involved, the XPNDR-term vanishes too.

For simplicity, we define a *Common Clock Difference* CCD(i) for each site:

$$\mathrm{CCD}(i) = +0.5\ \mathrm{TI}(i) + \mathrm{REFDLY}(i) - 0.5\ \mathrm{TI(PES)}_i - \mathrm{REFDELAY(PES)}_i. \quad (2)$$

With this definition (1) for the two sites becomes respectively:

$$0 = \mathrm{CCD}(1) + 0.5\ \mathrm{CALR}(1) - 0.5\ \mathrm{CALR(PES)}_1 \quad (3)$$
$$0 = \mathrm{CCD}(2) + 0.5\ \mathrm{CALR}(2) - 0.5\ \mathrm{CALR(PES)}_2. \quad (4)$$

Even though it can be assumed that that there will be a single constant, CALR(PES), valid for both sites 1 and 2, this set of two equations has three unknowns: CALR(1) and CALR(2) and CALR(PES). It is therefore not possible to solve for the all unknowns individually. Nevertheless, one can express the two CALR(i) in (1) as a function of CCD(i) and CALR(PES). With this substitution, one can then perform a time transfer experiment between two remote sites according to equation 1. It is a property of this calibration technique that in this way the third unknown CALR(PES) cancels from the general equation. The remaining terms can all be determined by other means. The final result of the calibration campaign involving two sites is thus expressed by:

$$\mathrm{CALR}(1, 2) = +0.5\ C_{\mathrm{Sagnac}}(1, 2) - \mathrm{CCD}(1) + \mathrm{CCD}(2). \quad (5)$$

The Sagnac correction for the link between site 1 and site 2 $C_{\mathrm{Sagnac}}(1, 2)$ depends on the geometry between earth stations and satellite. Details on how the Sagnac values for a single station are computed can be found in [6]. In preparation of the Galileo IOV, one calibration campaign is scheduled during which the two PTFs and four European timing institutes will be visited, namely INRIM (IT), LNE SYRTE (Observatoire de Paris), NPL (UK), and PTB. It has been shown that such calibrations can be performed with a combined uncertainty ≤1 ns [4,12]. In very few cases, a recalibration of a link with the same hardware still in place was conducted which would be necessary to verify that the calibration values are really unchanged with time. One example is the link between United States Naval Observatory (USNO) and PTB which is was calibrated eight times up to 2007 [14]. A recalibration of the links involved in Galileo is tentatively scheduled one year later, and has to be planned – technically and contractually – for the FOC phase of Galileo operations.

CONCLUSION

We investigated relevant operational parameters, as noise during regular TWSTFT sessions, C/N_0 as a function of Tx/Rx-power, chip rates of the pseudorandom noise, and their impact on the TWSTFT measurement precision and accuracy with the following results:

1) TWSTFT through a "quiet" transponder channel leads to a DRMS reduction by a factor of 1.4.
2 The frequency transfer capability is reduced at short averaging times by the same amount, but not significantly reduced at averaging times of > 1 day.
3) Higher Tx power increases C/N_0 but causes interferences with other stations' signals. This calls for strict discipline in operation of the links at fixed power levels.

Our final conclusion is that the two Galileo PTFs can be included in the network of stations and all requirements on the TWSTFT performance can be met. The increased complexity of the measurement schedule can be handled, and the increase in the noise level will still be compliant with the Galileo requirements. The required accuracy of time comparisons can be obtained by sufficiently frequent calibration of the links.

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