Studies on Measurement Noise in the European TWSTFT Network

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***Abstract*— Two-way satellite time and frequency transfer (TWSTFT) using geo-stationary telecommunication satellites is widely used in the timing community nowadays and has also been chosen as primary means to effect synchronization of elements of the ground segment of the European satellite navigation system Galileo. We investigated the link performance in a multi-station network in dependence on operational parameters, such as the number of simultaneously transmitting stations, transmit and receive power, and chip rates of the pseudo random noise modulation of the transmitted signals with the following results:**

- **TWSTFT through a "quiet" transponder channel (two stations transmitting only) leads to a measurement noise, expressed by the 1pps jitter, reduced by a factor of 1.4 compared to a busy transponder carrying signals of 12 stations.**
- **The frequency transfer capability expressed by the Allan deviation is reduced at short averaging times by the same amount.**
- **At averaging times of > 1 day no such reduction could be observed, which points to the fact that other noise sources dominate at such averaging times.**
- **Higher transmit power increases the carrier-to-noise density ratio at the receive station and thus entails lower jitter but causes interference with other stations' signals.**
- **The use of lower chip rates which could be accommodated by a reduced assigned bandwidth on the satellite transponder is not recommended. The 1pps jitter would go up by a factor of 2.5 when going from 2.5 MCh/s to 1 MCh/s.**

The two Galileo PTFs can be included in the currently operated network of 12 stations in Europe and all requirements on the TWSTFT performance can be met, provided that suitable ground equipment will be installed in the Galileo Ground Segment.

I. 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 future European satellite navigation system Galileo, as well as to support the measurement of the time difference between GPS time and the Galileo system time [2]. 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. The Galileo requirements regarding the measurement precision – less than 1 ns for a measurement duration of 2 minutes – and accuracy – 1 ns over an extended period – are quite demanding. In this contribution we discuss to which extent they can probably be fulfilled in such a dense network of simultaneous comparisons. For each pair of stations under consideration, e. g. PTF1 and PTF2, the signal of all other stations contribute to the measurement noise. It is thus of special interest to quantify the impact of an increased number of participating stations on a clock comparison between two laboratories and thereof to derive which the critical operational parameter limits are. This question is also important in view of the need for comparisons between primary frequency standards, which should ideally be made with a measurement uncertainty well below 1×10^{-15}.

After a very brief repetition of theoretical background of TWSTFT, we report on studies to discuss the following questions: To which extent do additional stations contribute to the measurement noise? Which is the tolerable range of the stations' transmission power, and what happens if a single station transmits with larger than nominal power? Among the changes that bear the potential for improvement of the

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TWSTFT method is the use of a phase modulation of the carrier with a higher PRN chip rate. Although this would require negotiations with satellite providers on the allocation of bandwidth on the satellite(s) at least temporarily and presumably higher cost of the transponder lease, some results obtained when higher chip rates were still permitted to be used are given which could guide further decisions in this respect.

II. BACKGROUND

Currently TWSTFT is made using fixed satellite services in the Ku-band and the X-band. It is done by transmission of pseudo random noise binary phase shift keying (BPSK) modulated carriers, phase connected to a local clock's one pulse per second (1pps) output. Each station uses a dedicated code with a defined BPSK sequence in its transmitted signal, and the receive equipment allows to generate the BPSK sequence of the remote stations and to reconstitute the lpps 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 have been discussed in [3].

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 analysing the 1pps output of the modem, corresponding to 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. The modems for modulating and de-modulating the signals in the 70 MHz intermediate frequency band are based on technology originally developed by Hartl et al. [4] (MITREX modem). In [4] a functional description of the expected 1pps jitter from C/N_0 at a given BPSK chip rate is given. The SATRE modem which is widely used today includes improved signal processing technology and provides a reduced 1 pps 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 [5], significantly less than stated in [4].

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. As in the ITU–R Recommendation TF.1153-2 [6] it is designated DRMS throughout this paper. We interpret the white-noise phase jitter in Fig. 1 as the classical standard deviation about the mean, typically denoted as σ_x. Thus from these data the relative frequency instability – expressed by the Allan standard deviation- can be calculated according to the relation $\sigma_y(\tau)=\sqrt{3}\times\sigma_x(\tau)/\tau$, as first proposed by Howe [7]. It should be clear that this relation governs the capability of making frequency comparisons between remote clocks only to

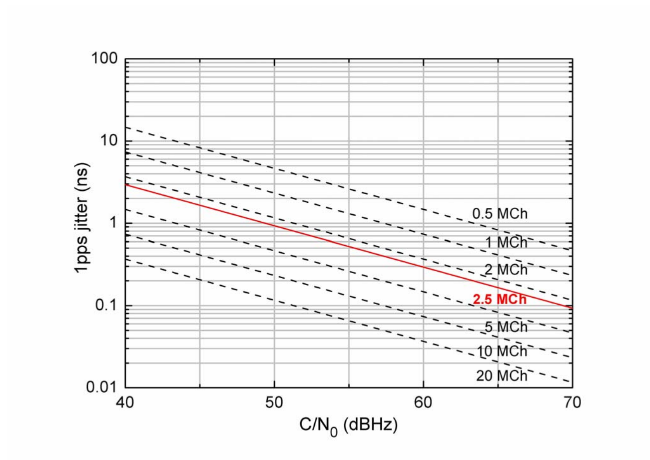

Figure 1. SATRE modem measurement noise (1pps jitter) as a function of C/N_0 after Hartl et al. [4] and Schäfer [5] for different chip rates (0.5 MCh/s to 20 MCh/s).

the extent that variations in the signal delay of the ground and space equipment and along the propagation path are insignificant. It is thus interesting to record short term jitter data and extrapolate to averaging times of several hours or days. As for such extended measurement periods the instability of the local frequency standards may become dominant, it has been common practice to form double differences between results obtained with independent techniques. Such data have been included in Fig. 2 as yellow and green squares: double differences GPS carrier phase – TWSTFT between various sites obtained in previous studies [8, 9]. Surprisingly, these data are even somewhat below the prediction based on the modem measurement noise. In Fig. 2 the solid line represents expected performance based on the data shown in Fig. 1 for 2.5 MCh/s received at C/N_0 = 55 dBHz. The red dots represent recent 1pps ranging data obtained as part of a regular European TWSTFT session, the blue dots are generated from secondly TWSTFT data collected for about 8 hours when two complete TWSTFT stations were

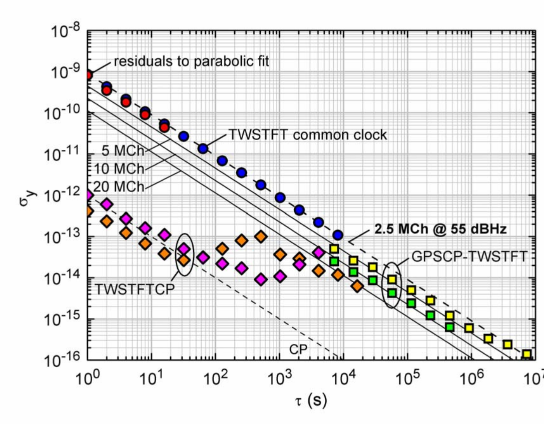

Figure 2. TWSTFT frequency stability data from the literature [8,9] and predicted theoretical values according to [5,7].

operated side-by-side connected to the same reference clock using a TWSTFT link with uplink and downlink frequencies in X-band [10].

Additional data show results of first TWSTFT carrier phase experiments which have the potential to provide a frequency stability of $\sigma_y = 10^{-12}$ at $\tau = 1$ s. A first study [11] shows good agreement with the predicted performance up to 100 s for common clock TWSTFT (orange diamonds) as well as for transatlantic TWSTFT between USNO and PTB (pink diamonds). However for longer averaging times the stability is decreased significantly and appears to be limited by other noise sources than just measurement noise.

III. 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 of a day. During the odd hours usually no TWSTFT experiments were 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 an individually assigned transmission frequency, then a ranging measurement is made during which each station receives its own signal and then the scheduled comparisons starts. Transmission of clean carrier 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 METAS and PTB.

IV. Experimental Results

A. *Noise during regular TWSTFT sessions*

The European TWSTFT network comprises 12 laboratories as shown in Fig. 3. In this configuration 6 pairs of laboratories can compare their time scales simultaneously. This means, that one station has to lock on the code of one remote station while in the full constellation 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.

At first we study the 1pps jitter observed during ranging measurements at PTB. 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 11 of 12

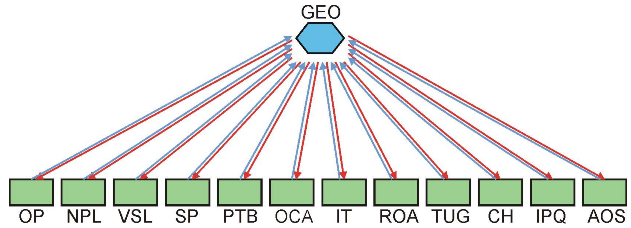

Figure 3. The European stations of the US/European TWSTFT network. U.S. laboratories are NIST an USNO, but not further mentioned here since reception of signals from the U.S requires another receive frequency. CH is the TWSTFT station acronym for METAS and used here and in the text.

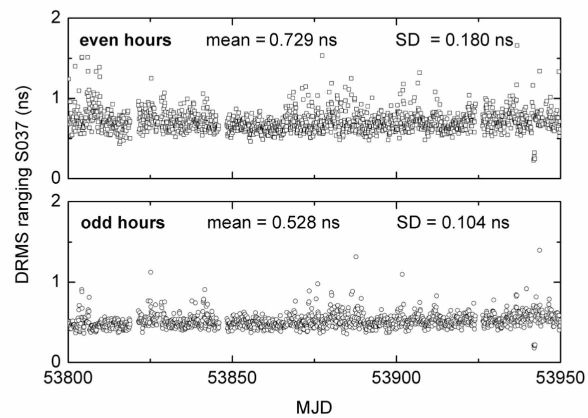

Figure 4. DRMS values of ranging measurements at PTB (S037) during the period MJD 53800 to MJD 53950 sorted for even (11 stations on air) and odd (2 stations on air) hour measurements

stations were transmitting, "on air", during the odd hour measurements 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 of 1.4.

TABLE I. Summary of the DRMS value comparison from measurements during even and odd hours. Note that due to the schedule not all stations are transmitting during the two minutes of CH-PTB comparisons.

		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***

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

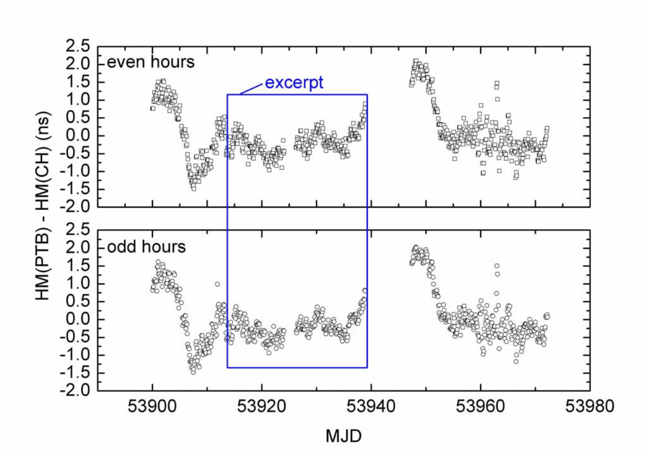

Figure 5. H-maser comparison between CH and PTB (S037) via regular TWSTFT. A second order polynomial is subtracted from the raw data.

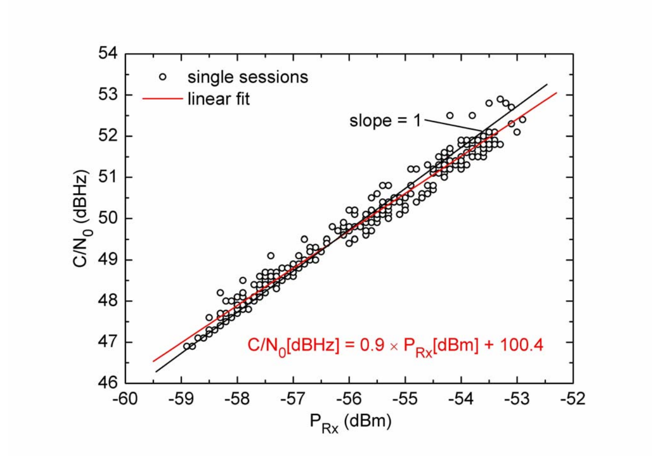

Figure 7. C/N_0 as a function of Rx power during ranging measurements with S280.

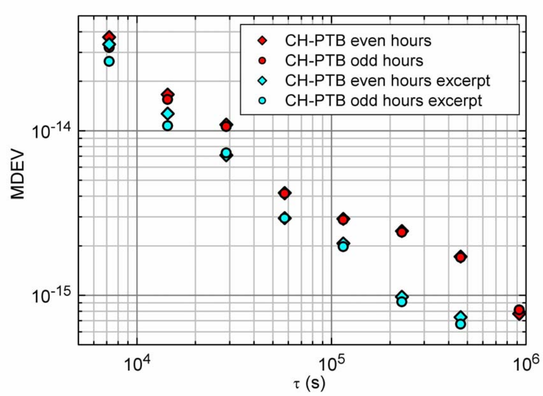

Figure 6. Relative frequency instability in terms of Modified Allan Deviation (MDEV) for the H-maser comparison data as depicted in Fig. 5.

values were slightly higher during the odd hours, explaining the smaller DRMS values determined at the same time.

We expected also an improvement of the instability of a frequency transfer for longer averaging times under the same experimental conditions. In order to test this, two hydrogen masers at METAS and PTB, respectively, were compared during the period MJD 53900 and MJD 53970 (see Fig. 5). The modified Allan deviations for even (diamonds) and odd (dots) hour measurements are displayed in Fig. 6 for the whole period (red symbols) and for an excerpt of the data during a period of quiet operation of the masers (blue symbols). When comparing the stability of the odd hour with the even hour measurements, at short averaging times (2 to 4 hours) the instability is indeed reduced. However, we observe no significant improvement at longer averaging times.

B. 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. 7 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. 8 the DRMS values for both received signals are displayed. As expected, the S037 DRMS values (black) 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 (red) 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.

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. 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

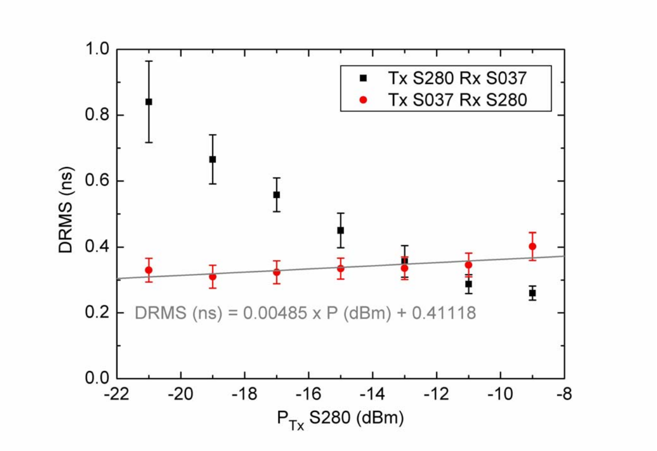

Figure 8. DRMS values for common clock TWSTFT measurements as a function of the variation of the Tx power of one modem (S280), while the modem S037 provided the same Tx power level throughout the experiments.

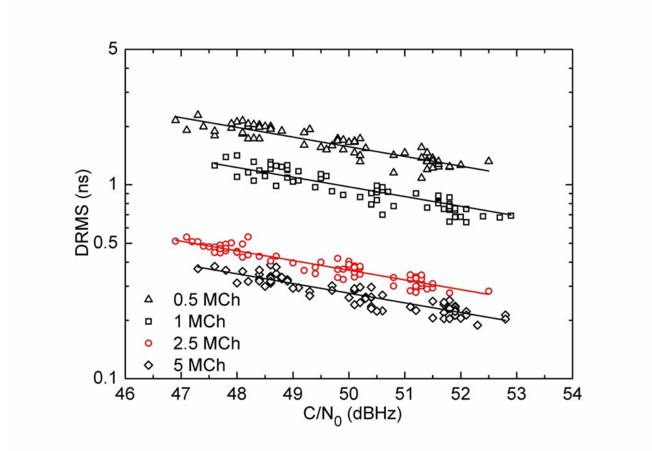

Figure 10. DRMS values of ranging measurements at PTB (S280) using different chip rates. Data were recorded in early 2006 using modem S280 during odd hours.

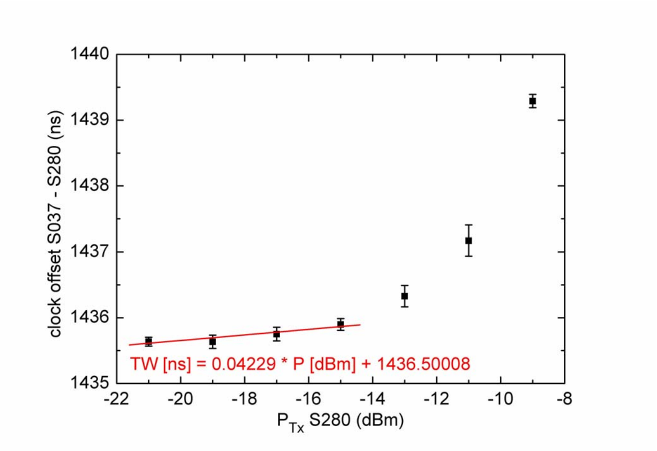

Figure 9. Common clock time comparison results when varying the transmission power in one of the modems (S280). The constant offset from zero is due to missing calibration of the S280 delays when taking these data.

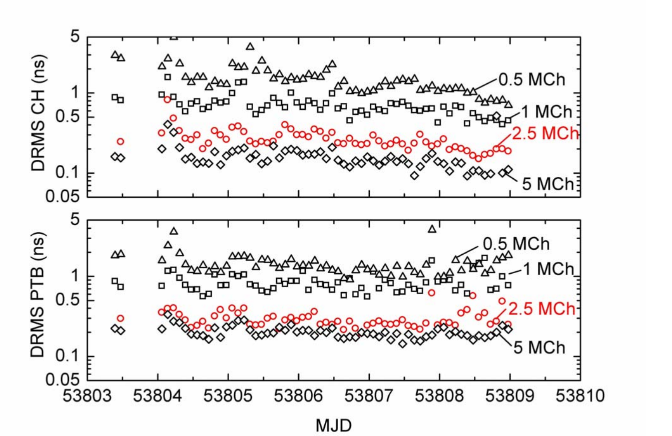

Figure 11. DRMS values of TWSTFT measurements between METAS and PTB (S280) using different chip rates in March 2006.

configuration. However, it was reported before that strong disturbing signals (even if they use different PRN codes) can introduce interferences in time transfer measurements [12]. We plan to repeat similar tests during extra TWSTFT measurements with a remote station.

C. *TWSTFT measurement noise as a function of PRN chip rates*

Since August 2006 the TWSTFT operations are governed by a lease contract with Intelsat General Corporation in which the allocated bandwidth is fixed at 3.5 MHz. This limits the BPSK chip rate to be 2.5 MCh/s or less. Before that date, the TWSTFT community had the chance to operate on an otherwise scarcely used transponder for many months, and could operate with larger chip rates for experimental purposes. During that period several studies were made, and some results are presented subsequently.

In Fig. 10 DRMS values for ranging measurements at PTB are depicted as a function of the received C/N$_0$ employing different chip rates at fixed transmission power. Taking 2.5 MCh/s chip rate as a reference the switch to a chip rate of 5 MCh/s reduces significantly the DRMS value while lower chip rates (1 MCh/s, 0.5 MCh/S) increase the short term noise dramatically.

The measured DRMS values in TWSTFT sessions between METAS and PTB (see Fig. 11) show a similar dependency on the used chip rate. While for smaller rates the noise increases to inadmissible values, there is still significant improvement when going from 2.5 MCh/s to 5 MCh/s. The averaged DRMS values for the received CH-signal at PTB were reduced from 0.30 ns to 0.20 ns.

A reduction of the chip rate reduces the occupied bandwidth and it would thus be a chance to reduce the cost of TWSTFT operations, because the lease fee for a transponder is proportional to the occupied bandwidth. But we strongly propose not to go that way since the benefits of TWSTFT would be compromised thereby. In contrary, the challenge of comparing primary frequency standards which have a relative frequency instability of far less than 1×10^{-15} at one day averaging and uncertainties in the low 10^{-16} range would motivate to test higher chip rates at least on an experimental basis since that would reduce the short term noise for the price of a wider bandwidth occupied on the transponder.

V. 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 pseudo random 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 (ADEV or MDEV) is reduced at short averaging times by the same amount.

3) MDEV is not significantly reduced at averaging times of > 1 day.

4) 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.

5) The use of lower chip rates to save bandwidth on the satellite transponder is not recommended. DRMS noise would go up by a factor of 2.5 when going from 2.5 MCh/s to 1 MCh/s.

A last 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 following a practice as described in [13].

For a future improvement of the TWSTFT performance, one strategy is to reduce the background noise to achieve higher C/N_0 values by limiting the number of transmitting stations for a certain period. We showed that on short measurement durations the noise is thereby significantly decreased while there is no clear improvement for averaging times of one day and longer. Such a measure could be envisaged during pre-scheduled campaigns of comparisons between primary frequency standards. Another solution is the use of higher chip rates which has proved to yield lower noise values – up to now only at short averaging times. However, higher chip rates require a broader bandwidth on the leased satellite transponder, whose lease cost exceeds in general the financial possibilities of the timing community at present. Another issue is the verification of the benefit of such a measure. Either one would need to make comparisons between frequency standards of proven exceptional long term frequency stability or one would need to arrange GPS carrier phase frequency comparisons to be made in parallel, in a similar way as demonstrated in 2005 [8].

References

[1] B. Guinot and F. Arias, "Atomic time keeping from 1955 to the present", Metrologia, vol. 42, pp. S20-S30, 2005.

[2] R. Hlavác, M. Lösch, F. Luongo and J. Hahn, "Timing infrastructure for Galileo system," Proc. 20th European Frequency and Time Forum, 2006, pp. 391–398, 2006.

[3] D. Kirchner, "Two-way Satellite Time and Frequency Transfer (TWSTFT): Principle, implementation, and current performance", Review of Radio Sciences 1996-1999, Oxford University Press 27-44, 1999.

[4] P. Hartl et al., „High accuracy global time transfer via geosynchronous telecommunication satellites with Mitrex," Z. Flugwiss. Weltraumforsch, vol. 7, pp. 335-342, 1983.

[5] W. Schäfer, Time Tech GmbH, Stuttgart, Germany, private communication 2007.

[6] Recommendation ITU-R TF.1153-2, "The operational use of two-way satellite time and frequency transfer employing PN timing codes",, Geneva, last update 2003.

[7] D. A. Howe, "Progress toward one-nanosecond two-way time transfer accuracy using Ku-band geostationary satellites," IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, vol. 34, pp. 639-646, November 1987.

[8] A. Bauch et al., "Comparison between frequency standards in Europe and the USA at the 10^{-15} level," Metrologia, vol. 43, pp. 109-120, 2006.

[9] C. Hackman, J. Levine and T.E. Parker, "A long-term comparison of GPS carrier-phase frequency transfer and two-way satellite time/frequency transfer," Proc. 38th Precise Time and Time Interval (PTTI) Systems and Applications Meeting, December 2006, Washington, DC, USA, in press.

[10] D. Piester et al., "Time transfer between USNO and PTB: operation and calibration results," Proc. of the 35th PTTI San Diego, USA, pp. 93-101, 2004. Data were recorded during the USNO calibration campaign in March 2007.

[11] B. Fonville, D. Matsakis, A. Pawlitzki, and W. Schäfer, "Development of Carrier-Phase-Based Two-Way Satellite Time and Frequency Transfer (TWSTFT)," Proc. 36th Precise Time and Time Interval (PTTI) Systems and Applications Meeting, December 2004, Washington, DC, USA, pp. 149-164, 2005.

[12] T. Parker:, "NIST Station Report", CCTF working group on TWSTFT meeting, Paris, September 10-12, 2006.

[13] D. Piester et al., "Calibration of six European TWSTFT earth stations using a portable station," Proc. of the 20th EFTF Braunschweig, Germany, pp. 460–467, 2006.