Report of CCTF WG on Two-Way Satellite Time and Frequency Transfer (TWSTFT) to the 19th Session of the CCTF

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Introduction

Since the 18th CCTF Meeting in 2009, much has happened in the area of TWSTFT. As in many areas of science and technology there has been expansion, development, modification and transformation. As the role of TWSTFT is important to the BIPM in the acquisition of clock data, many laboratories are interested in preserving, maintaining and improving the services that are provided by TWSTFT. In the corresponding period we have seen a further growth in the worldwide use of TWSTFT. 23 partners in America, Asia and Europe are participating actively in this network. This network is divided into 3 regional sub-networks (Europe/USA, Asia/Pacific Rim, and Asia/Europe) maintaining TWSTFT links among the participating stations via dedicated telecommunication satellites. Time transfer data are recorded continuously 7 days a week throughout the year. In addition, a link between Asia and USA has been established enabling a connectivity of regions around the world.

Organization and maintaining these networks, e.g. the purchase of satellite transponder time and data handling, are sometimes demanding tasks, especially during times when operational changes have to be made and all participating stations have to prepare their hard- and software at the same time.

Along with the expansion of the use of TWSTFT data, we have also seen a significant improvement in TWSTFT techniques and data analysis. We noted the use of new modulation techniques, the exploitation of the carrier phase, and investigations into limiting factors of the TWSTFT performance. Observed instabilities at the level of or below 10^{-12} at 1 s averaging time make these new developments attractive for a meaningful comparison even of optical atomic clocks as well as back-up methods or as benchmark for alternative advanced time and frequency transfer experiments, such as the future ACES microwave link or the use of optical fibers.

Status of the Europe/USA TWSTFT Network

In the Europe/USA network one satellite is used to connect sites between NIST (Boulder, USA) in the West and AOS (Poznan, Poland) in the East. By the end of 2009 the satellite used at that time (IS-3R) reached the end of its useful life. The only known alternative satellite that can provide the necessary coverage has been Telstar 11-N. Due to significant increase of transponder costs the use of a lower chiprate (1 Mcps instead of 2.5 Mcps) was investigated in order to reduce the occupied bandwidth. Tests showed that there has been only a modest degradation in performance for most links by using a lower chiprate [Zhang2010]. Therefore it was decided to purchase a bandwidth of 2.5 MHz which is adequate for the 1 Mcps codes and allows further testing with 2.5 Mcps codes in combination with band-pass filters. The contract was made with AGS for the time July 2009 until July 2010. The option of prolongation was asserted until July 2011 on the same conditions. Tests with 2.5 Mcps and SAW-filters result in a small improvement for longer averaging times but noise of the SAW filter contributes to the short term time-transfer instability [Zhang2011]. A further need for cost reduction resulted in purchasing only 1.7 MHz in Europe and 1.6 MHz for transatlantic TWSTFT. The new contract has been made with RiteNet Corp. starting from July 2011 with the option of yearly prolongation and nominally identical conditions for 4 years and the chiprate is now fixed to 1 Mcps. The change of contract partner necessitated a change of the transmission frequencies, and thus a recalibration of the TWSTFT links for the production of TAI was necessary [Jiang2011].

Regular measurements in the Europe/USA network are undertaken between AOS, INRiM, IPQ, LNE-SYRTE, METAS, NIST, NPL, PTB, PTF1 and PTF2, OCA, ROA, SP, TIM, TUG, USNO, and VSL in bi-hourly comparisons during 1 hour, mainly for the production of TAI. During the regular comparisons a considerable number of stations transmit at the same time, which increases the background noise and which is a potential cause for interference. A significant improvement of the short-term noise on the two-way links was achieved by the introduction of offsets into the transmitted frequencies. The free second hour (the bi-hourly schedule) is reserved for experiments because during that time a quiet transponder (with only a very limited number of stations transmitting) reduces the measurement noise significantly. Tests have shown an excellent stability of 40 ps at 1 d is obtained using the regular 1 Mcps modulation on the OP-PTB link.

Status of Asia/Pacific Rim TWSTFT Network

The Asia/Pacific Rim link had been established by the satellite, IS-8 (166° E), until the end of March 2011. Due to the end of the lifetime of IS-8, subsequently the North East Asia beam of the satellite GE-23 (172° E) was used, beginning in April 2011. Later the link shifted to the North Pacific beam of GE-23 in April 2012 for reduction of the satellite link fee. The Asia/Pacific Rim link is carried on using the same frequency allocation as that for the Asia-Hawaii link at present. The time-transfer measurements are regularly performed once per hour by using NICT modems. The current participating stations are NICT, TL and NICT's domestic stations.

NICT and USNO established the USNO-Hawaii-Asia link using a relay station in Hawaii in July 2010. It consists of two links; USNO-Hawaii link via AMC-1 and Asia-Hawaii link via GE-23 North Pacific beam. Currently NICT and TL connect to USNO once every hour. The time-transfer measurements are performed by using SATRE modems. Thanks to a hydrogen maser at the Hawaii station, the link stability in the 10^{-15} level for frequency transfer at one day has been achieved. A disagreement at the ns level with GPS time transfer is sometimes observed, however. The link quality has been monitored carefully.

Status of Asia/Europe TWSTFT Network

The Asia-Europe link had been established by the satellite, IS-4 (72° E), until the end of January 2010. Unfortunately the link stopped due to the malfunction of IS-4. After two test measurements, the link was re-established using the satellite AM-2 (80° E), in October 2010. Since the coverage is more limited than before, the only current participating stations in Europe are PTB and VNIIFTRI. From

Asia, NICT, TL, NIM, NTSC and NPLI have participated. The working time of the transponder is from 13:00 UTC to 23:00 UTC only. During the periods of operation, the time-transfer measurements are performed for five minutes every hour by using SATRE modems. The data are reported to BIPM regularly. NICT-PTB and TL-PTB links have been adopted as links for calculation of TAI. It is said that the AM-2 has little time left to function. The switch to another satellite has been under consideration.

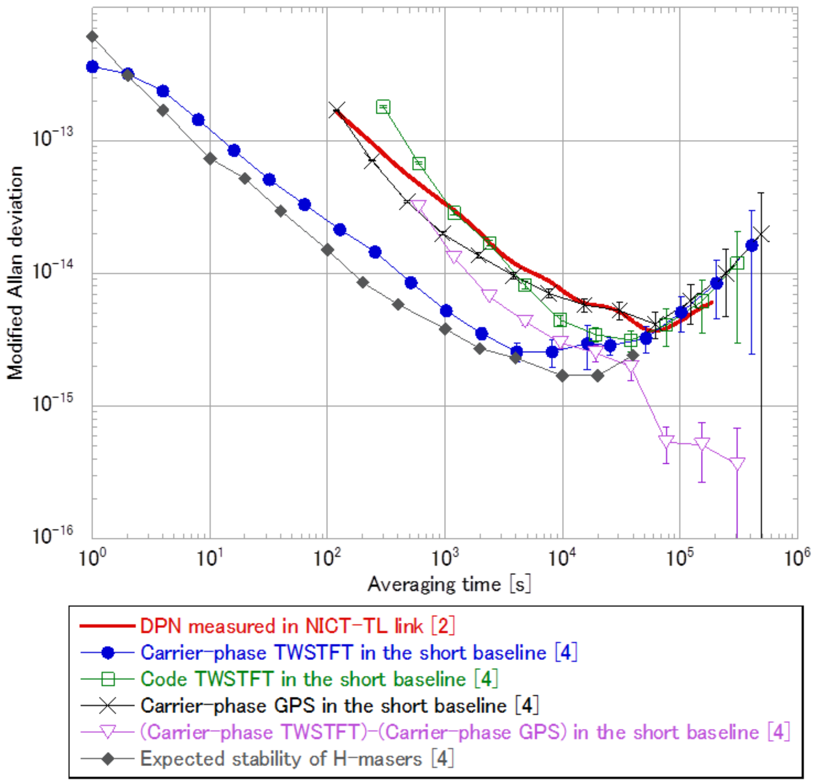
In the previous link via IS-4, clear diurnal variations with 1-ns (or more) amplitude had been observed. We concluded that they might be caused by the asymmetric paths in the used transponders [Fujieda2011]. In the current link via AM-2, such a variation hasn't occurred so far, at least it is less pronounced. It may be attributed to the symmetric path thanks to the use of only one transponder, on the other hand the limited operation time masks diurnal effects.

New developments in TWSTFT

Dual pseudo-random noise and TWSTFT carrier phase

NICT has developed TWSTFT using dual pseudo-random noises (DPN), where two coded signals with a lower chip rate are used with separately-allocated frequencies. In this scheme, spreading the signals with a gap frequency is equivalent to using a wider chip rate signal. A measurement precision of 16 ps was achieved using 128-kbps coded signals with a frequency separation of 20 MHz [Gotoh2011]. NICT and TL have occasionally performed DPN TWSTFT on the link by GE-23 North East Asia beam and the achieved time transfer stability is shown in the following figure [Tseng2012].

For further improvement of the measurement precision, NICT has started the development of carrier-phase-based TWSTFT [Fujieda2012]. In the short baseline with a length of 150 km, the measurement precision of 0.4 ps was achieved and the time variation showed good agreement with the results of GPS carrier phase. The following figure shows the resultant frequency instabilities. The evaluation in a longer baseline is planned as a next step.



Also at OP the implementation of the carrier phase technique led to a significant improvement of the measurement noise: frequency stability of 1x10-12 at 1 s and 3x10-14 at 100 s were obtained with OP01 and OP02 in collocation [Kanj2012]. However, a degradation of the stability is observed at 300 s. Further investigations are in progress.

Other activities

Implementations of satellite simulators for an absolute station calibration were investigated at OP and VSL [Mubarak2012]. A characterization of the OP01's differential delay resulted in 400 ps expanded uncertainty (k = 2).

Beside measurement noise, which is directly related to the link design, TWSTFT exhibits limitations by showing a diurnal pattern of the time transfer result in a number of links. These observations are still under investigation and procedures for an improvement of operational links have been tested lately by TL [Tseng2011],[Huang2011].

Also operational TWSTFT plays an important role as a reference time and frequency transfer method for experimentation and testing advanced techniques as Time Transfer by Laser Link (T2L2) [Samain2011].

Calibrations and data handling

For the production of TAI measurement data are provided by the individual participating stations following the ITU Recommendations ITU-R TF.1153-2 [ITU2003]. The need for an update and a redefinition of reporting observables led to a new directive for operational use and data handling in two-way satellite time and frequency transfer [Bauch2011]. BIPM also reorganized their internal

TWSTFT data handling [Jiang2010] and developed a procedure to identify potential outlier in the provided measurement data [Harmegnies2010].

A calibration campaign coordinated by ROA between three contributing laboratories was organized using a travelling GPS receiver: ROA (Spain), PTB (Germany) and INRIM (Italy). The time transfer results were achieved by using P3 and also carrier phase PPP data, and they were also used to re-calibrate the TWSTFT links between labs [Esteban2010]. PTB has supported this project and has developed a mobile GPS calibration unit [Feldmann2011] which was used in calibrations involving METAS (2009), USNO (2010), NPL (2010), NICT (2011), and BKG (2011), of which the first 3 laboratories are equipped with TWSTFT. Each of the campaigns provided a calibration of all existing links between the visited institutes and PTB with a an uncertainty (1 σ) of the order 1.2 ns which is considered valid at the epoch of the campaign. ROA is about to conduct a second repetition of the initial campaign to study the reproducibility of results.

USNO has continued to support calibrations of the link between USNO and PTB. In addition to the GPS-based calibration two calibrations using a fly-away TWSTFT terminal took place. The results were provided by USNO and are given in the table below. In the table, column 3 is the measured time difference at the epoch of the calibration, and column 4 is how much should be added to the value of USNO-PTB according to the current calibration. The combined uncertainty for each calibration is estimated to be about 1 ns (1 σ).

Table: Results of USNO-PTB calibrations.

MJD	Calendar Date	USNO-PTB	Cal-Circular T	Technique/Ref
55301	15 APR 2010	-19.1 ns	-1 ns	GPS [Feldmann2011]
55649	29 MAR 2011	0.1 ns	+2 ns	TWSTFT
56072	25 MAY 2012	0.8 ns	+1 ns	TWSTFT

Participating Stations

America:

NIST, USNO

Asia:

NICT, NIM, NMIJ, NPLI, NTSC, TL

Europe:

AOS, CH (METAS), IPQ, IT (INRIM), NPL, OCA, OP, PTB, PTF1 (ESA), PTF2 (ESA), ROA, SP, SU (VNIIFTRI), TIM (TimeTech), TUG, VSL

Meetings of the CCTF WG on TWSTFT

Annual Meetings:

17th Meeting, 20th and 21st October 2009, Poznań, Poland,

18th Meeting, 16th and 17th September 2010 NIM, Beijing, PR China

19th Meeting , 12th and 13th September 2011, NMIJ, Tsukuba, Japan

20th Meeting, 6th and 7th September 2012, BIPM, Sèvres, France

Participating Stations Meetings at Conferences:

41st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 16-19 Nov 2009, Santa Ana Pueblo, New Mexico, USA

24th European Frequency and Time Forum, 13-16 April 2010, Noordwijk, The Netherlands

42nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 15-18 Nov 2010, Reston, Virginia, USA

43nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 14-17 Nov 2011, Long Beach, CA, USA

25th European Frequency and Time Forum, 24-26 April 2012, Gothenburg, Sweden

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