Report of the CCTF Working Group on Two-Way Satellite Time and Frequency Transfer

May 2017

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I. Overview

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is one of the accurate and high precise time transfer techniques used in UTC generation. It uses geostationary satellites to relay timing signals from reference clocks of the remote TWSTFT stations. At present, the timing signals are carried by pseudo-random noise (PRN) codes. The TWSTFT equipment on each side of a TWSTFT link measures the time difference of its transmit signal and the received signal. By differencing the measurements from each side with corrections of the delays in the reference signal paths and in the TWSTFT signal propagation paths, we obtain the time and frequency differences of the two remote clocks. The accurate and precise TWSTFT results are available in near real time. TWSTFT is independent of and complementary to the GNSS time transfer.

As of today, more than 20 timing laboratories around the world actively participate in TWSTFT. TWSTFT data involving Asia/Asia, Asia/Europe, Europe/Europe and Europe/USA are gathered by the BIPM, and 12 TWSTFT links are used in the UTC generation. The Circular T assigns about 1 ns Type B uncertainties (u_B) and about 0.5 ns Type A uncertainties (u_A) to the TWSTFT links. However, the TWSTFT differences of most links contain a daily variation (diurnal) with magnitude up to 2 ns peak-to-peak. Over the past years, several studies were conducted in searching for the causes of the diurnal, but no dominant cause could be found. The diurnal is the main instability of TWSTFT.

Thanks to the great effort and support from TWSTFT participating stations and the BIPM, several successful TWSTFT link calibrations using TWSTFT mobile stations and GPS calibrators were carried out since the 20th CCTF Meeting in 2015. The calibrations showed most of the UTC TWSTFT links were as stable or more stable than their assigned link calibration uncertainty (1 to 1.5 ns).

In early 2016, the Working Group (WG) on TWSTFT originated a task group to investigate the long-term instability of GPS and TWSTFT links. Many WG members participated in the task group study, together with members of the WG on GNSS Time Transfer. The study lead to a paper at the 2016 ION-PTTI meeting and the proposal for a Recommendation "On the Utilization and Monitoring of Redundant Time Transfer Equipment in Timing Laboratories Contributing to UTC" jointly prepared by the WGs on GNSS Time Transfer and on TWSTFT, which will be presented during this meeting.

In February 2016, the BIPM and the WG on TWSTFT organized a pilot study of using Software Defined Radio (SDR) receivers for TWSTFT. The SDR TWSTFT was first proposed and tested on the Asia/Asia links. The results showed significant reduction of diurnals in the TWSTFT differences. The aim of the pilot study is to investigate the impact of SDR TWSTFT using different satellites for the Asia/Europe, Europe/Europe and Europe/USA links. All of the laboratories operating TWSTFT expressed great interest of the study. As of May 2017, twelve laboratories have installed the SDR systems and participated in the regular daily SDR TWSTFT. In addition, several laboratories will soon install the SDR system. The pilot study showed that SDR TWSTFT can significantly reduce diurnals in most of the intra-continental TWSTFT links and reduce the short-term TWSTFT time transfer noise in all TWSTFT links.

Furthermore, members of the WG on TWSTFT and the BIPM studied the use of redundant data in TWSTFT network for improving the TWSTFT stability. Some of the TWSTFT participating laboratories are developing and testing digital TWSTFT modems for PRN coded and carrier-phase TWSTFT. Based on these studies and new developments, the WG on TWSTFT will propose the Recommendation "On Improving Two-Way Satellite Time and Frequency Transfer for UTC-Generation" to this CCTF meeting.

Details of the TWSTFT networks, TWSTFT link calibrations and WG activities will be reported below.

II. Status of the TWSTFT Networks (as of May 2017)

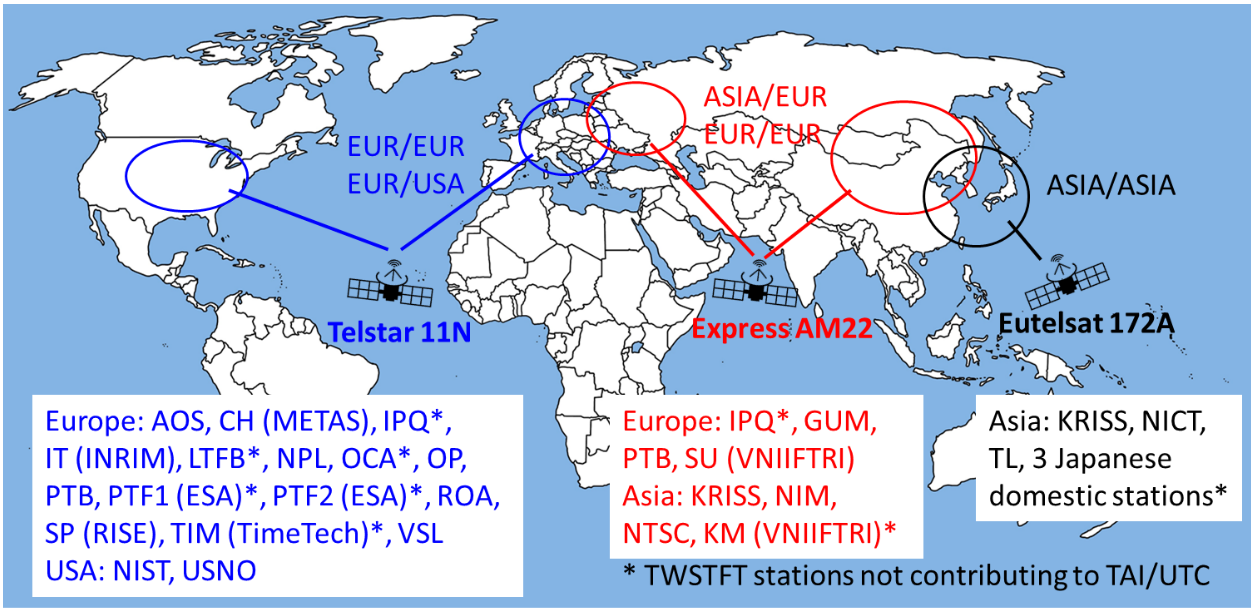

Figure 1. Summary of the regional and inter-continental TWSTFT networks.

II.1 Regional and inter-continental networks

In the Europe/Europe and Europe/USA networks, the Telstar 11N (T-11N) satellite is used to connect sites between NIST (Boulder, USA) in the west and AOS (Poznan, Poland) in the east. The network uses three Ku-band transponders on the satellite, one for the Europe/Europe links with 1.7 MHz bandwidth, one for the Europe/USA and one for the USA/Europe links each with 1.6 MHz bandwidth. The TWSTFT signals are carried by 1 Mchip/sec PRN codes, and the TWSTFT measurements for each link are made in a 2-minute session in every even UTC hour every day. A new satellite contract was signed by NIST and PTB for using the T-11N satellite between 27 November, 2016 and 26 May, 2021. The cost of the satellite contract is shared by participating stations.

In the Asia/Europe and Europe/Europe network, the Express AM22 satellite is used to connect sites between PTB (Braunschweig, Germany) in the west to KRISS (Daejeon, South Korea) in the east. The network uses one Ku-band transponder on the satellite with 2.5 MHz bandwidth. The TWSTFT signals are carried by 2.5 Mchip/sec PRN codes. The TWSTFT measurements for each links are made in at least one 5-minute session per hour every day. The cost of the satellite contract is shared by participating stations. Starting in November 2016, the AM22 satellite went into an increasingly inclined orbit. At the end of May 2017, it reached the same inclination level as the previously used AM2 satellite when the TWSTFT was stopped. VNIIFTRI is leading the efforts of finding a replacement satellite for the Asia/Europe and Europe/Europe network to continue the TWSTFT.

The Asia/Pacific regional TWSTFT network includes participating stations of NICT, KRISS, TL, and three Japanese domestic stations. The 2 Mchip/sec PRN TWSTFT signals go through a Ku-band transponder with 2.5 MHz bandwidth on the E172A satellite. The TWSTFT measurements are made hourly. The satellite contract is managed by NICT and funded by Japanese government. This situation will continue for some years.

II.2 Participating Stations and Members of the WG:

Asia: BIRMM*, KRISS, NICT, NIM, NIMJ, NPLI, NTSC, TL

Europe: AOS, CH (METAS), GUM, IPQ*, IT (INRIM), LTFB*, NPL, OCA*, OP, PTB, PTF1 (ESA)*, PTF2 (ESA)*, ROA, SP (RISE), SU (VNIIFTRI), TIM (TimeTech)*, VSL

U.S.A.: NIST, USNO

* participating stations not contributing to TAI/UTC computations.

III. Calibrations

After NIST implemented the results of the BIPM 2014-2015 calibration campaign, as detailed in the TM256, on 28 April, 2016 (MJD 57506), all of the UTC TWSTFT time links and non-UTC TWSTFT time links since the 20th CCTF meeting were calibrated up to that date.

From 4 April to 3 June, 2016, ROA coordinated a Europe/Europe TWSTFT link calibration campaign with the TimeTech Ku-band mobile station. Table 1 shows the calibrated links and the calibration results.

Table 1. Summary of the 2016 calibrations of Europe/Europe TWSTFT links. (All values are given in ns)

Link	CALR(old)	CALR(new)	CALR variation	E_n
PTB – INRIM (IT01)		+708.02		
PTB – INRIM (IT02)	+982.90	+981.25	-1.65	0.66
PTB – OP	+7820.20	+7820.15	-0.05	0.02
PTB – ROA	+675.20	+674.70	-0.50	0.23
PTB – SP	+707.30	+707.89	+0.59	0.26
OP – INRIM (IT01)		-7112.16		
OP – INRIM (IT02)	-6837.30	-6839.07	-1.77	0.68
OP – ROA	-7145.00	-7145.61	-0.61	0.29
OP – SP	-7112.90	-7112.20	+0.70	0.33
ROA – INRIM (IT01)		+33.86		
ROA – INRIM (IT02)	+307.70	+306.44	-1.26	0.52
ROA – SP	+32.10	+33.61	+1.51	0.69
SP – INRIM (IT01)		+0.29		
SP – INRIM (IT02)	+275.60	+271.92	-3.68	1.48

Note:

- CALR was calculated taking into account that ESDVAR will be re-set to zero.
- $E_n = \frac{|CALR(new) - CALR(old)|}{\sqrt{(U\_CALR^2 + U\_CALR\_old^2)}}$; (U_CALR=*2* x ***uc***); $E_n \leq 1$ consistent (95%).

The PTB/USNO Ku-band UTC TWSTFT link was calibrated with the USNO X-band mobile station in August 2016. The estimated uncertainty was 0.7 ns (1-sigma) and a calibration correction of 0.4 ns was implemented on 25 October, 2016 (MJD 57686).

The USNO Ku-band mobile station, together with a USNO GPS calibrator, calibrated the UTC(NIST) – UTC(USNO) on 15 February, 2017 (MJD 57799). The discrepancy of the UTC(NIST) – UTC(USNO) obtained from the TWSTFT calibration and that obtained from the triangle TWSTFT difference of NIST/PTB – USNO/PTB is 0.8 ns, which is within the uncertainty of the mobile station calibration uncertainty.

IV. Development and Activities

IV.1 Update of TWSTFT Calibration Guidelines

The "TWSTFT Calibration Guidelines for UTC Time Links" was approved by the WG on TWSTFT during the 23rd annual meeting in 2015. Based on the experience from the implementations of the BIPM 2014-2015 calibration campaign, a revision of the guidelines was initiated to describe the procedure for implementation of new calibration in more details. The guidelines were updated accordingly and approved by the WG during the 24th annual meeting in 2016.

IV.2 Task group study on "Long-Term Instability of UTC Time Links"

The task group study on "Long-Term Instability of UTC Time Links" was originated by the WG on TWSTFT in early 2016, and published in the BIPM TM263 and in a 2017 ION-PTTI paper. The study was triggered by observations reported by NIST and OP during the 23rd annual meeting that TWSTFT difference and GPS difference of the NIST/PTB and OP/PTB links drifted apart significantly with respect to the estimated link uncertainty over the years as shown in Figures 2 and 3. The task group members come from the WGs on TWSTFT and on GNSS Time Transfer.

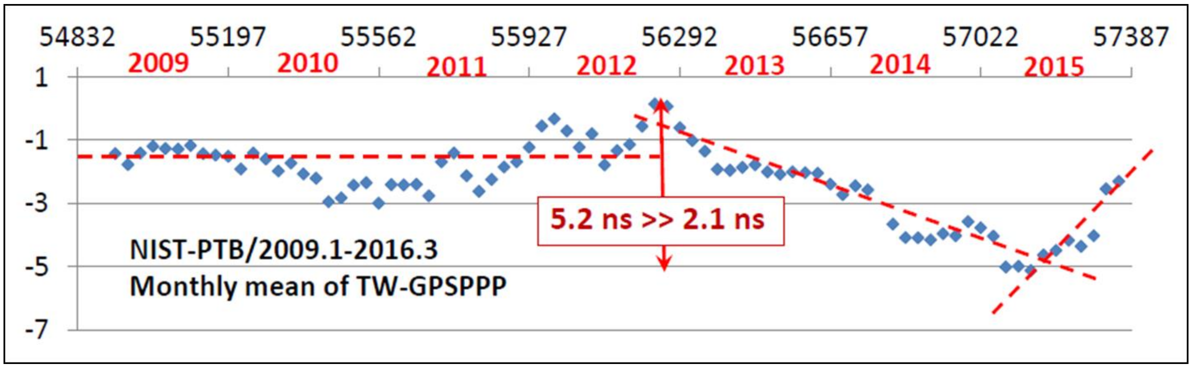

Figure 2. Seven-year Double-Clock Difference (DCD) of TWSTFT – GPSPPP for the NIST/PTB baseline. The vertical axis is for DCD in ns, and the horizontal axis is for MJD in days. The estimated uncertainty of the NIST/PTB link was 2.1 ns during the data period.

In the task group study, we analyzed

(1) the Common-Clock Differences (CCD) among co-located GPS receivers that use reference signals from the same local clock,

(2) Double-Clock Differences (DCD) of different time transfer links over the same baseline,

(3) calibration results for evaluation of the long-term link instability,
(4) correlations between the link instabilities and environment factors, hardware changes and changes of the setup and lab operation.

Figure 3. Seven-year Double-Clock-Difference of TWSTFT – GPSPPP forr the PTB/OP baseline.

The study found that many elements are indicative of or contributing to the long-term instability of UTC time links, such as seasonal variations in some DCD of TWSTFT – GPSPPP, the change of reference signals for a GPS receiver causing a time step in GPS time transfer results, the change of the antenna and antenna cable shared by two GPS receivers resulting in a time step in CCD of the two receivers, the aging of the antenna and antenna cable introducing a drift in the signal delay, etc. The study concluded that

- several-ns variations happen too often to ignore; they are observed in GNSS-only, TWSTFT-only, and GNSS-TWSTFT;
- past performance is not a reliable indicator of future stability;
- multiple independent GNSS systems are crucial;
- calibrations should be conducted yearly, a GNSS calibration can be complementary to a TWSTFT calibration, especially if they are done at the same time;
- environmental control is important;
- more attention must be given to recording configuration changes and environmental conditions.

These findings are reflected in the proposal of a recommendation of "On the Utilization and Monitoring of Redundant Time Transfer Equipment in the Timing Laboratories Contributing to UTC" prepared jointly by the WGs on GNSS Time Transfer, and on TWSTFT.

IV.3 Pilot study on using Software Defined Radio (SDR) receivers for TWSTFT

The daily variation (diurnal) in the TWSTFT difference is the main instability for most of the TWSTFT links. Over the past years, several studies were conducted in searching for the causes of the diurnal, but no dominant cause could be identified. The SDR TWSTFT uses a SDR receiver that works side-by-side with the currently used TWSTFT equipment (SATRE) and utilizes the same reference signals as for SATRE. The SDR receiver measures the difference between timing of its reference signal and the timing of the received signal transmitted by the remote SATRE. The use of SDR receivers for TWSTFT was first proposed and tested on the Asia/Asia links. The results showed significant reduction of diurnals in the TWSTFT differences as shown in Figure 4.

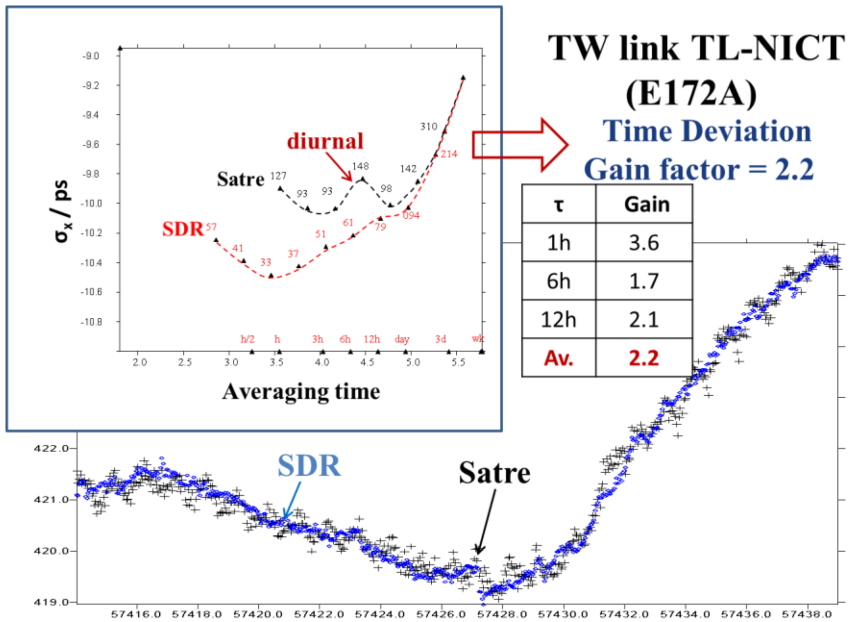

Figure 4. Improvement of SDR TWSTFT for the Asia/Asia TWSTFT link.

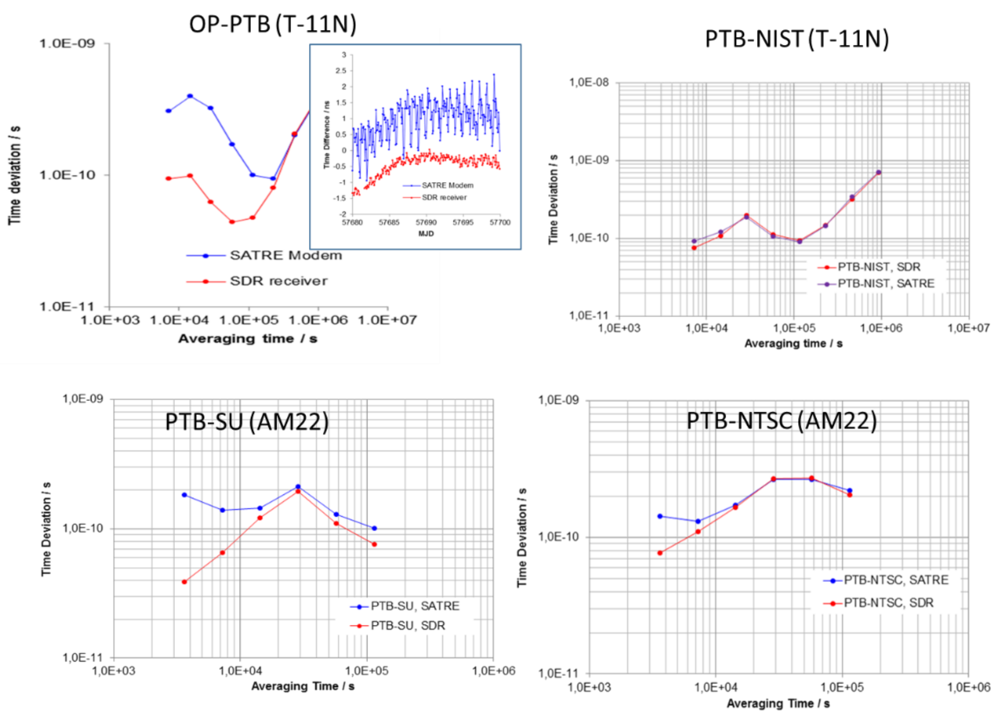

Figure 5. Examples of the improvement from SDR TWSTFT on using different satellites for Europe/Europe (OP/PTB and PTB/SU), Europe/USA (PTB/NIST) and Europe/Asia (PTB/NTSC) links.

In early 2016, the BIPM and our WG started a pilot study. The aim of the pilot study is to investigate the impact of SDR TWSTFT on using different satellites for the Asia/Europe, Europe/Europe and Europe/USA links. All of the laboratories operating TWSTFT showed great interest of the study. As of

May 2017, twelve laboratories have installed the SDR system and participated the regular daily SDR TWSTFT. Several laboratories will soon install the SDR system. The pilot study showed the SDR TWSTFT can significantly reduce diurnal in most of the intra-continental TWSTFT links and reduce the short-term TWSTFT time transfer noise in all TWSTFT links. The examples of the improvement from SDR TWSTFT are shown in Figure 5. The SDR TWSTFT results were recently published in the proceedings of the 2017 ION-PTTI meeting and will be again reported at the upcoming joint meeting of the IFCS and EFTF.

IV.4 Study on using redundant TWSTFT data for improving stability of TWSTFT links

In TWSTFT networks, there are UTC time links (the links to PTB) and many non-UTC time links that are redundant links in the view of UTC generation. Other redundant time transfer data, such as TW + GPSPPP, have been used for UTC generation to improve the stability of UTC time links. Two studies have found that instabilities of the Europe/Europe UTC TWSTFT links can be reduced with the transatlantic indirect TWSTFT links as shown in Figure 6. More studies are necessary for using the redundant TWSTFT data in UTC generation.

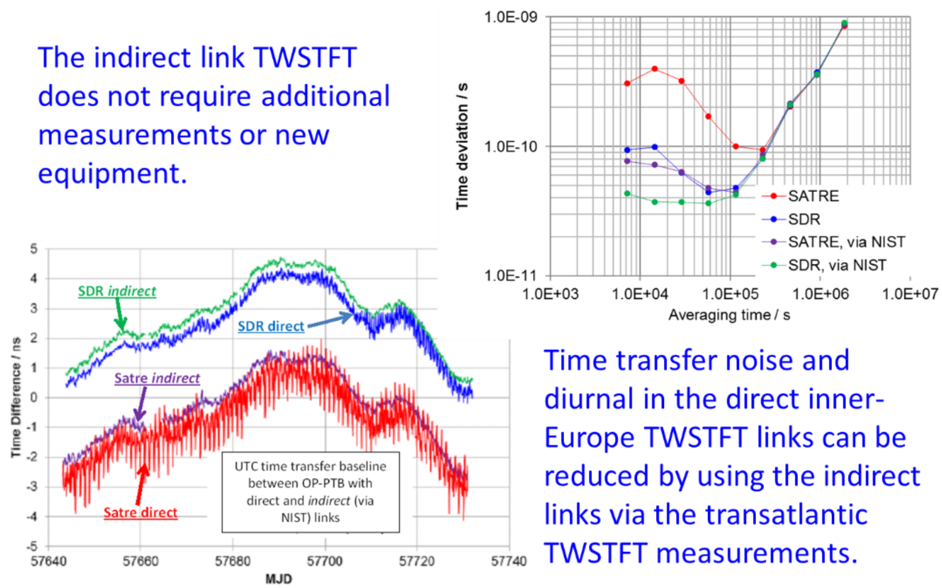

Figure 6. Improved Europe/Europe TWSTFT stability with redundant transatlantic TWSTFT measurements.

IV.5 Development of new digital modem

Some TWSTFT participating laboratories are developing and testing digital TWSTFT modems for PRN coded and carrier-phase TWSTFT. Because the Ku-band carrier frequency is much higher than the GPS L-band carrier frequency, in theory, the carrier-phase TWSTFT could achieve measurement resolution much higher that of the GPS carrier-phase. Figures 7-8 show the bench test results of the digital modem under development at NICT.

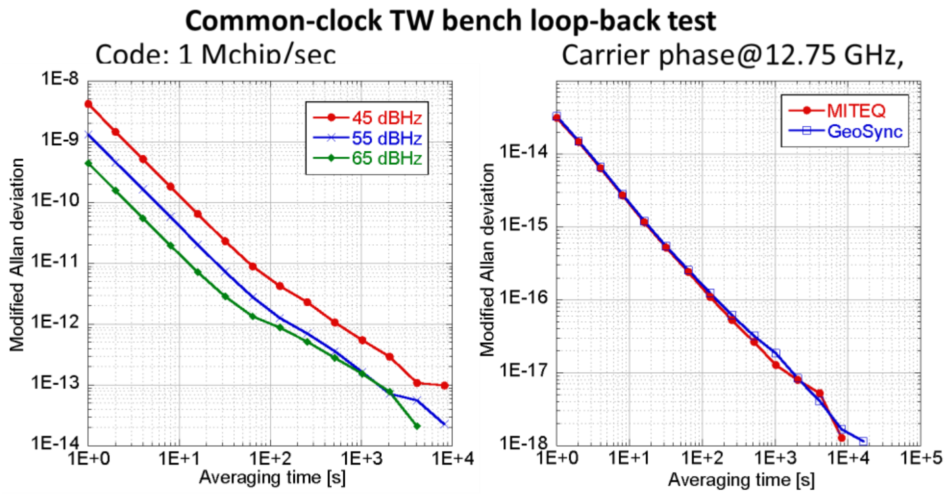

Figure 7. Common-clock TWSTFT bench loop-back test results of the NICT digital modem.

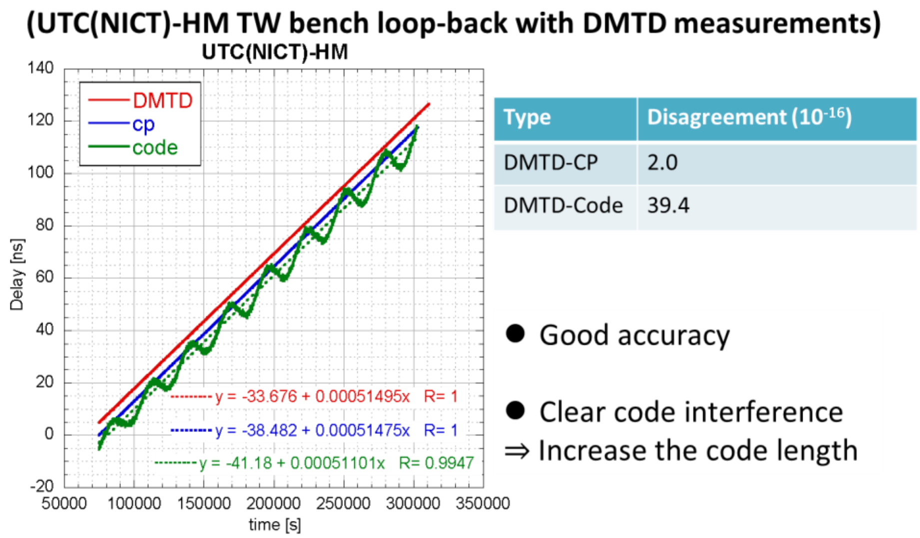

Figure 8. Comparison of the Dual-Mixer Time Difference (DMTD) measurements and the TWSTFT bench loop-back test of the NICT digital modem.

Based on the SDR pilot study results, the studies on using redundant TWSTFT data and the development on digital modems, the WG on TWSTFT will propose a Recommendation "On Improving Two-Way Satellite Time and Frequency Transfer for UTC-Generation" to this CCTF meeting.

IV.6 Meetings

Annual meetings:
- 24th Meeting, 7-8 September, 2016, NIST, Boulder, Colorado, U.S.A.
- 25th Meeting, 18-19 May, 2017, NTSC, Xi’an, China

Participating stations meetings at conferences:
- PTTI 2016, 25-28 January, 2016, Monterey, California, U.S.A.
- 30th EFTF, 4-7 April, 2016, York, United Kingdom
- PTTI 2017, 30 January – 2 February, 2017, Monterey, California, U.S.A.