



Recommendation ITU-R TF.1153-4
(08/2015)

**The operational use of two-way satellite
time and frequency transfer
employing pseudorandom noise codes**

TF Series
Time signals and frequency standards emissions



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Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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RECOMMENDATION ITU-R TF.1153-4

**The operational use of two-way satellite time and frequency transfer
employing pseudorandom noise codes**

(Question ITU-R 250/7)

(1995-1997-2003-2010-2015)

Scope

TWSTFT has been recognized as the most precise and accurate means for remote clock comparisons and is thus widely used in the time and frequency community, including institutions and organizations affiliated with telecommunication administrations. In view of the progress in performance of the atomic clocks compared via TWSTFT it was found necessary to calculate corrections applied to the measurement results with a higher accuracy than considered necessary in previous editions. As the Earth is not perfectly spherical, it is considered as an ellipsoid at first approximation. For a given location, there are a single longitude and two latitudes: the geocentric latitude and the geodetic latitude. The current version takes proper care of this in the calculation of the Sagnac correction.

Keywords

Two way satellite time and frequency transfer, TWSTFT, CDMA, Sagnac correction, timescale comparison

The ITU Radiocommunication Assembly,

considering

- a) the demonstrated high-accuracy for time and frequency comparisons using the two-way satellite time and frequency transfer (TWSTFT) method as expressed in Question ITU-R 250/7;
- b) the well-established use of TWSTFT systems in global networks using telecommunication satellites, predominantly in the Ku band (10.7-14.5 GHz), in support of, but not limited to, the realization of Coordinated Universal Time (UTC);
- c) that other frequency bands are becoming important;
- d) that some TWSTFT links have been repeatedly calibrated so that time transfer with a systematic uncertainty below 1 ns can be achieved;
- e) that theoretical background is available to calculate the corrections for the effect of the propagation delay through the troposphere and the ionosphere, the correction for the Sagnac-effect, and other reciprocity factors;
- f) that TWSTFT is nowadays performed in networks with more than ten participating stations using code division multiple access (CDMA);
- g) the need for standardizing:
 - measuring procedures;
 - data processing;
 - formats for the exchange of data and relevant information between participating stations and interested bodies, such as the International Bureau for Weights and Measures (BIPM),

recommends

- 1 that the measuring and data processing procedures for accurate time and frequency transfer via TWSTFT be followed as outlined in Annex 1;
- 2 that the data formats for the exchange of the relevant data between participating stations and interested bodies should be as outlined in Annex 2.

Annex 1

Procedures for TWSTFT

1 Introduction

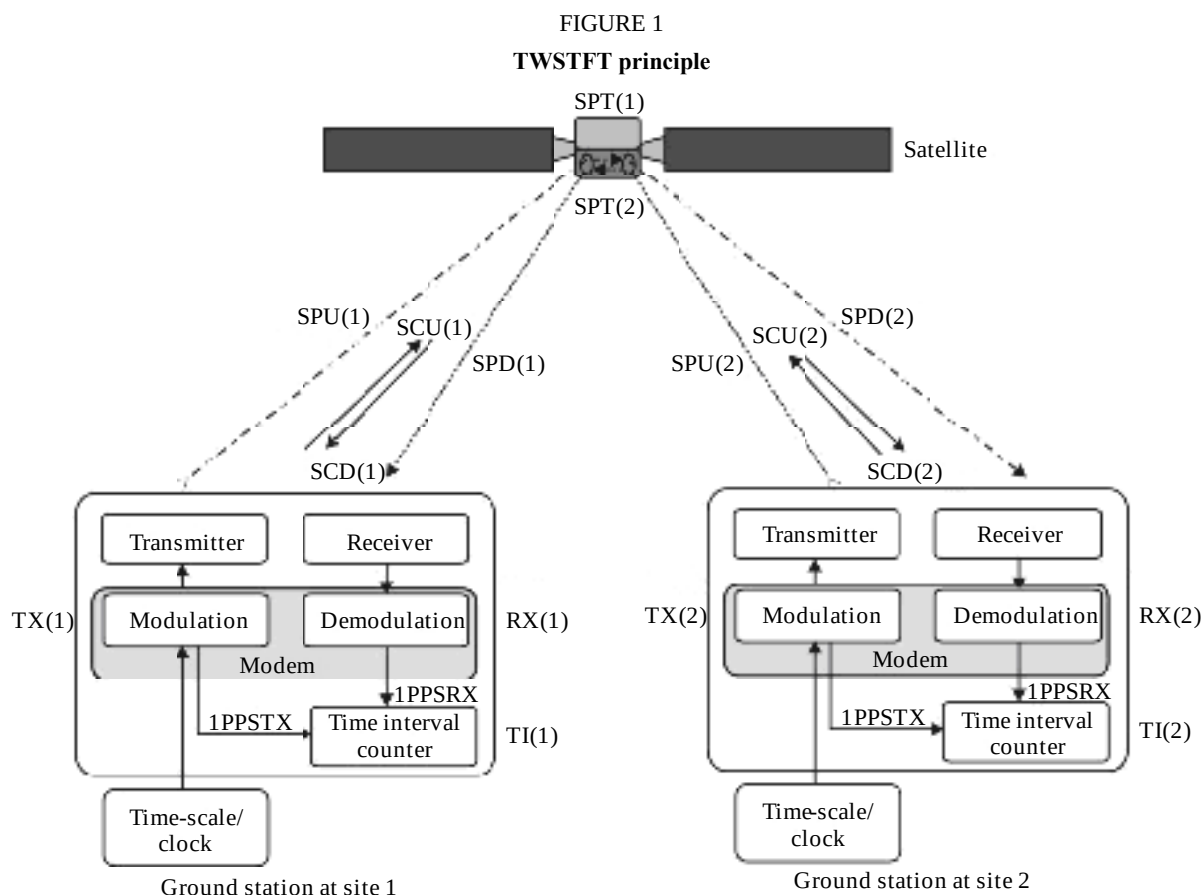
TWSTFT using geostationary telecommunication satellites has been proven to be the most appropriate means of comparing time-scales and atomic frequency standards with an uncertainty in time of less than 1 ns and with relative uncertainty for frequency of about 1 part in 10^{15} at averaging times of one day. This is why TWSTFT is widely used in the international network of time-keeping institutions supporting the realization of International Atomic Time (TAI) and UTC by the International Bureau for Weights and Measures (BIPM, Bureau International des Poids et Mesures). Such activities are performed under the auspices of the Working Group on TWSTFT of the Consultative Committee for Time and Frequency (CCTF). For the same reasons, TWSTFT has *inter alia* been chosen or proposed as the primary means to synchronize the elements of the ground segment of global navigation satellite systems. Many other applications can be envisaged. This Recommendation builds on well-established practice currently in use in networks comprising institutes in Europe and the United States of America, in Europe and Asia, and also within the Asia-Pacific Region, operating in support of the BIPM. It shall, however, remain sufficiently open to adapt for new applications and services.

Radio links have been used to transfer time from one clock to another for a long time. In radio links, however, the signal delays are changing with distance, ionosphere, troposphere, temperature, earth conductivity and so on. To cancel these influences to first order the two-way scheme has been introduced: at both clock sites the time signals are transmitted at nominally the same instant and on both sides the signal from the other clock is received and its time of arrival is measured. After the exchange of the measured data, the difference of the two clocks is calculated. The delays cancel due to the reciprocity, to first order, of the signal paths. The accuracy of the result then depends on the residual effects due to the incomplete reciprocity. Some of these effects are well understood and others are still under study. In some cases corrections for these effects can be used to improve accuracy.

2 Brief description of the exchanged signals

TWSTFT is based on the exchange of timing signals through geostationary telecommunication satellites, as is schematically shown in Fig. 1. It is done by transmission and reception of radio-frequency (RF) signals, containing pseudorandom noise (PRN) codes binary phase-shift keying (BPSK) modulated on the intermediate frequency (IF) by a modem. The phase modulation is synchronized with the local clock, and the modem generates a one-pulse-per-second (1PPS) output, synchronous with the BPSK sequence, and named 1PPSTX. This signal is the realization of a time-scale named TS(k). Each station uses a dedicated PRN code for its BPSK sequence in the

transmitted signal. The receiving equipment generates the BPSK sequence of the remote stations and reconstitutes a 1PPS tick from the received signal, named 1PPSRX. The difference $TI(k)$ between the two 1PPS signals is measured by a time-interval counter (TIC). Following a pre-arranged schedule, a pair of stations lock on the code of the corresponding remote station for a specified period, called a session, measure the signal's time of arrival, and store the results. After exchanging the data records the difference between the two clocks can be computed. In the remainder of Annex 1, details of the data reduction and the treatment of systematic effects are elaborated.



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Figure 1 illustrates the various signal delays and explains how the time difference between the clocks at stations 1 and 2 can be determined. The various acronyms have the following significance.

- TS(k): Local time-scale, physically represented by the 1PPSTX signal generated by the modem, k being 1 for station 1 and 2 for station 2
- TI(k): Time interval reading, the counter gate is opened by a 1PPS signal related to the local transmit signal and closed by a 1PPS signal related to the received signal; short-form designation of $1PPSTX - 1PPSRX$
- TX(k): Transmitter delay, including the modem delay
- RX(k): Receiver delay, including the modem delay
- SPU(k): Signal path uplink delay
- SPD(k): Signal path downlink delay
- SPT(k): Satellite path delay through the transponder
- SCU(k): Sagnac correction in the uplink
- SCD(k): Sagnac correction in the downlink.

The difference of the time-scale at station 2 from the time-scale at station 1 expressed by $TS(1) - TS(2)$ is determined as follows:

The TIC reading at station 1 is:

$$TI(1) = TS(1) - TS(2) + TX(2) + SPU(2) + SCU(2) + SPT(2) + SPD(1) + SCD(1) + RX(1)$$

The TIC reading at station 2 is:

$$TI(2) = TS(2) - TS(1) + TX(1) + SPU(1) + SCU(1) + SPT(1) + SPD(2) + SCD(2) + RX(2)$$

Subtracting the expression for station 2 from that for station 1, gives:

$$TI(1) - TI(2) = 2 TS(1) - 2 TS(2) + TX(2) - TX(1) + SPU(2) - SPU(1) + SPT(2) - SPT(1) + SPD(1) - SPD(2) + RX(1) - RX(2) + SCD(1) - SCU(1) - SCD(2) + SCU(2)$$

The time-scale difference is thus given by the so-called two-way equation:

$$\begin{aligned} TS(1) - TS(2) &= 0.5 [TI(1)] && (= \text{TIC reading at station 1}) \\ &- 0.5 [TI(2)] && (= \text{TIC reading at station 2}) \\ &+ 0.5 [SPT(1) - SPT(2)] && (= \text{Satellite delay difference}) \\ &- 0.5 [SCD(1) - SCU(1)] && (= \text{Sagnac correction for station 1}) \\ &+ 0.5 [SCD(2) - SCU(2)] && (= \text{Sagnac correction for station 2}) \\ &+ 0.5 [SPU(1) - SPD(1)] && (= \text{Up/down difference at station 1}) \\ &- 0.5 [SPU(2) - SPD(2)] && (= \text{Up/down difference at station 2}) \\ &+ 0.5 [TX(1) - RX(1)] && (= \text{Transmit/receive difference at station 1}) \\ &- 0.5 [TX(2) - RX(2)] && (= \text{Transmit/receive difference at station 2}). \end{aligned}$$

The last seven terms are the corrections for non-reciprocity. Except for the satellite delay difference SPT, the corrections can in principle be grouped in corrections per station.

The non-reciprocity factors are further addressed in the following sections.

3 Causes of non-reciprocity and systematic uncertainty in TWSTFT

3.1 Non-reciprocity due to satellite equipment delays

When the satellite receive antenna, transponder channel and transmit antenna are common to both signal paths, the satellite signal delays are equal, i.e. $SPT(1) = SPT(2)$. This is not the case when different frequencies, transponders or different spot beams are used for the reception and/or transmissions from each station, as is common for intercontinental links. In this case $SPT(1)$ and $SPT(2)$ or at least the difference $SPT(1) - SPT(2)$, designated as $XPNDR(k)$, should be measured before the launch of the satellite or using another accurate method.

3.2 Sagnac-effect correction

Due to the movement both of the earth stations and of the satellite around the rotation axis of the Earth during the propagation of a time signal to and from the satellite, a correction has to be applied to the propagation time of the signal. The Sagnac correction for the one-way path from satellite s to ground station k is given in a terrestrial reference frame which provides sufficient accuracy by:

$$SCD(k) = (\Omega / c^2) [Y(k) X(s) - X(k) Y(s)]$$

where:

$$\begin{aligned} X(k): & \text{ Geocentric x-coordinate of station (m)} \\ & = (a \cos[\tan^{-1}\{(1-f) \tan[LA_{geodetic}(k)]\}] + H(k) \cos[LA_{geodetic}(k)]) \cos[LO(k)] \\ X(s): & \text{ Geocentric x-coordinate of satellite (m)} \\ & = R \cos[LA(s)] \cos[LO(s)] \\ Y(k): & \text{ Geocentric y-coordinate of station (m)} \\ & = (a \cos[\tan^{-1}\{(1-f) \tan[LA_{geodetic}(k)]\}] + H(k) \cos[LA_{geodetic}(k)]) \sin[LO(k)] \\ Y(s): & \text{ Geocentric y-coordinate of satellite (m)} \\ & = R \cos[LA(s)] \sin[LO(s)] \\ c: & \text{ Speed of light} = 299\,792\,458 \text{ m/s} \\ \Omega: & \text{ Earth rotation rate} = 7.2921 \times 10^{-5} \text{ rad/s} \\ f: & \text{ Flattening of the Earth ellipsoid} = 1/298.257222 \\ a: & \text{ Earth equatorial radius} = 6\,378\,137 \text{ m} \\ R: & \text{ Satellite orbit radius} = 42\,164\,000 \text{ m} \\ LA(k): & \text{ Latitude of the station (rad)} \\ LO(k): & \text{ Longitude of the station (rad)} \\ H(k): & \text{ Height of the station (m).} \end{aligned}$$

As the Earth is not perfectly spherical, it is considered as an ellipsoid at first approximation. For a given location, there are a single longitude and two latitudes: the geocentric latitude and the geodetic latitude. To convert from geodetic to geocentric coordinate, the following formula is used:

$$LA_{geocentric}(k) = \tan^{-1} \left\{ \frac{(1-f) \sin[\tan^{-1}\{(1-f) \tan[LA_{geodetic}(k)]\}] + \left(\frac{H(k)}{a}\right) \sin[LA_{geodetic}(k)]}{\cos[\tan^{-1}\{(1-f) \tan[LA_{geodetic}(k)]\}] + \left(\frac{H(k)}{a}\right) \cos[LA_{geodetic}(k)]} \right\}$$

For geostationary satellites $LA(s) = 0^\circ$ N, so:

$$SCD(k) = \frac{\Omega}{c^2} R (a \cos[\tan^{-1}\{(1-f) \tan[LA_{geodetic}(k)]\}] + H(k) \cos[LA_{geodetic}(k)]) \sin[LO(k) - LO(s)]$$

The total Sagnac correction $SCT(1,2)$ for a measurement of the clock at station 2 with reference to the clock in station 1 is:

$$SCT(1,2) = 0.5 [SCU(1) + SCD(2) - [SCU(2) + SCD(1)]]$$

Furthermore, the sign of the Sagnac correction for the downlink is opposite to the sign of the Sagnac correction for the uplink due to the opposite propagation directions of the signals: $SCU(k) = -SCD(k)$, so that $SCT(1,2) = -SCD(1) + SCD(2)$ is valid.

Example for a satellite at 43° W (317° E):

$$LA(VSL) = 51^\circ 59' 8'' \text{ N}, LO(VSL) = 4^\circ 23' 17'' \text{ E}, \text{ difference in } LO = 47^\circ 23' 17'', H(VSL) = 76.8 \text{ m}, SCD(VSL) = + 99.10 \text{ ns}$$

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$LA(\text{USNO}) = 38^\circ 55' 14'' \text{ N}$, $LO(\text{USNO}) = 77^\circ 4' 0'' \text{ W}$, difference in $LO = -34^\circ 4'$, $H(\text{USNO}) = 46.9 \text{ m}$, $SCD(\text{USNO}) = -95.22 \text{ ns}$

$SCT(\text{VSL} \rightarrow \text{USNO}): -SCD(\text{VSL}) + SCD(\text{USNO}) = -194.32 \text{ ns}$

$SCT(\text{USNO} \rightarrow \text{VSL}): -SCD(\text{USNO}) + SCD(\text{VSL}) = +194.32 \text{ ns}$

VSL: Delft, the Netherlands, previously known as NMi Van Swinden Laboratory

USNO: US Naval Observatory, Washington DC, United States of America.

The position of a geostationary satellite is not perfectly fixed with respect to the observer on Earth. A small periodic motion with a daily period occurs around a central position. This causes a periodic variation of the Sagnac effect with a maximum peak to peak amplitude of a few hundred ps depending on the location of the participating stations. This has been mostly ignored up to now, but needs to be accounted for if particularly high accuracy is aimed at.

3.3 Path delay difference due to satellite movement in an Earth fixed frame

Two-way paths between earth stations via the satellite are not reciprocal if the satellite is in motion relative to the Earth's surface and if the two arriving signals do not pass through the satellite at the same instant. This effect can in principle be avoided by an offset between the emission times at the two stations to compensate for the different path delays SPU(1) and SPU(2) to the satellite. If the signals from the two stations arrive at the satellite within 5 ms, the delay difference is at the level of only a few tens of ps, and it shows a diurnal pattern.

3.4 Ionospheric correction

The uplink and downlink signals at each station differ in carrier frequency and they experience a different ionospheric delay equal to:

$$40.3 \text{ TEC } (1/c) (1/f_d^2 - 1/f_u^2)$$

where:

the coefficient 40.3 is in the unit of m^3/s^2

TEC: Total Electron Content along the signal path (unit: electrons/ m^2)

c : speed of light (m/s)

f_d and f_u : downlink and uplink frequencies (Hz), respectively.

Example: For a high TEC of 1×10^{18} electrons/ m^2 and $f_u = 14.5 \text{ GHz}$ and $f_d = 12.5 \text{ GHz}$ this ionospheric delay is equal to $0.859 \text{ ns} - 0.639 \text{ ns} = 0.220 \text{ ns}$. So the difference $0.5[\text{SPU}(k) - \text{SPD}(k)]$ is typically smaller than -0.11 ns .

3.5 Tropospheric correction

The troposphere gives a delay depending on the elevation angle, the water content of the air, air density and temperature, but up to 20 GHz this delay is only frequency dependent to a very small extent. So its influence on the difference between the up and down propagation delays is $< 10 \text{ ps}$.

3.6 Earth station delay measurement

The difference of the transmit and receive section $[\text{TX}(k) - \text{RX}(k)]$ including the up and down converters, modulator and demodulator (modem), amplifiers, antenna, cabling, etc., has to be determined at each station. Methods to obtain this are: