BUREAU INTERNATIONAL DES POIDS ET MESURES

Directive for operational use and data handling in two-way satellite time and frequency transfer (TWSTFT)

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2011

Pavillon de Breteuil, F-92312 SEVRES Cedex

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Andreas Bauch*, Dirk Piester*, Miho Fujieda**, Włodzimierz Lewandowski***

    * Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
    ** National Institute of Information and Communications Technology (NICT), Tokyo, Japan
    *** International Bureau of Weights and Measures (BIPM), Sèvres, France

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1 Introduction

Two-way satellite time and frequency transfer (TWSTFT) [1] has been developed into a widely used technique of time and frequency transfer between laboratories that contribute, with their atomic clocks and, in some cases, with their primary frequency standards, to the realization of International Atomic Time (Temps Atomique International, TAI) [2]. The TWSTFT technique is thus used in two areas: for true time transfer, by comparing local time scales such as local realizations of Coordinated Universal Time (UTC(i)) in laboratories i, and for accurate frequency comparisons between atomic fountain clocks and hydrogen masers. At present, TWSTFT is performed operationally in at least two laboratories in the United States, twelve in Europe, and seven in the Asia Pacific region. The cooperation is organized by the CCTF Working Group on TWSTFT. For each of the regional networks, an administrator has been assigned who should be contacted before changes to the operational practice are made or when a new institute wishes to join. At the time of writing the regional administrators are Miho Fujieda (NICT) and Dirk Piester (PTB).

TWSTFT is performed in networks with multiple participating stations using code division multiple access (CDMA). From early on it was clear that there was a need to standardize the:

– measuring procedures,

– data processing, and

– formats for the exchange of data and relevant information between participating stations and interested bodies, such as the International Bureau of Weights and Measures (BIPM).

In this respect members of the ITU-R Study Group 7 (Working Party 7A) finalized a first version of a recommendation document as early as 1995.

In the present report we recapitulate the theoretical background of TWSTFT and derive the equations describing accurate time transfer. As far as possible and expedient we follow the description and names used in the latest version of ITU-R Recommendation TF.1153-2 [3], finalized in 2009. In the following section we give a list of the abbreviations and symbols used in the text and equations.

2 List of abbreviations and symbols

|	
BPSK	Binary phase-shift keying
CAL(i, k)	Calibration value, which has to be added to the raw TWSTFT measurement result between stations i, k to yield the true time difference between the clocks at stations i and k.
CCD(i, k)	Common-clock difference, TWSTFT measurement result between two TWSTFT set-ups (i, k) at one site, connected to the same clock
CDMA	Code division multiple access
CLOCK(i)	(Master) clock as the physical representation of an atomic time scale
C / N_0	Carrier-to-noise density
DLD(i)	Difference of signal propagation delay through the transmit and receive path of station i, TX(i) – RX(i)
EDV	Earth station delay variation, used to report known changes in the set-up of a TWSTFT ground station
EIRP	Equivalent isotropically radiated power
GEO	Geostationary satellite
IF	Intermediate frequency, typically 70 MHz
L	Designation of local laboratory by an ASCII character
LAB	Laboratory identification

P	Power level
PRN	Pseudo-random noise
PS	Portable Station, short name for a transportable TWSTFT ground station used in calibration experiments
R	Designation of remote laboratory by an ASCII character
REFDELAY(i)	Reference delay, time difference between the local time scale and the modem 1PPS output synchronous with its TX signal
RF	Radio frequency
RX(i)	Signal delay in the receive path of TWSTFT station i
SCD(i)	Sagnac delay for a signal propagating from the GEO satellite to station i
SCU(i)	Sagnac delay for a signal propagating from station i to the GEO satellite
SP(i)	Complete signal path delay from station i to station k through the GEO, SPU(i) + SPT(i) + SPD(k)
SPD(i)	Signal path downlink delay
SPU(i)	Signal path uplink delay
SPT(i)	Satellite path delay through the transponder from site i to site k
TAI	Temps Atomique International (International Atomic Time)
TIC	Time-interval counter
TI(i)	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
TS(i)	Local time scale, physically represented by the 1PPSTX signal generated by the modem, i being 1 for station 1 and 2 for station 2
TW(i)	Counter reading in the TWSTFT station i
TWSTFT	Two-way satellite time and frequency transfer
TX(i)	Signal delay in the transmit path of the TWSTFT station i
UTC(i)	Coordinated Universal Time as realized in laboratory i
XPNDR(i)	Differential transponder delay (ns), SPT(i) − SPT(k), corresponding to: local station i to remote station k minus remote station k to local station i
1PPS	One-pulse-per-second
1PPSREF	1PPS input to the modem
1PPSTX	1PPS output, synchronous with the BPSK sequence and named 1PPSTX
1PPSRX	Reconstituted 1PPS tick from the received signal

3 Procedures for TWSTFT

3.1 Brief description of the signals

TWSTFT is based on the exchange of timing signals through geostationary telecommunication satellites as is schematically shown in Fig. 1. It involves the transmission and reception of radio frequency (RF) signals carrying binary phase-shift keying (BPSK) modulations containing pseudorandom noise (PRN) codes. Modems designed specifically for the purpose generate the modulation at the intermediate frequency (IF) level which are then transmitted after up-conversion to the RF band (Ku-band or X-band are currently used). The received RF-signal is down-converted and the modem detects the modulation at the IF level. 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 represents the realization of a time scale named TS(k). Each station uses a dedicated PRN code for the BPSK sequence in its transmitted signal. The receiving equipment generates the BPSK sequence of the remote station and reconstitutes a 1PPS tick from the received signal, named 1PPSRX. The difference TI(k) between PPSTX and PPSRX (in general plus a constant) 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 this section, we give details of the data reduction and describe the treatment of systematic effects.
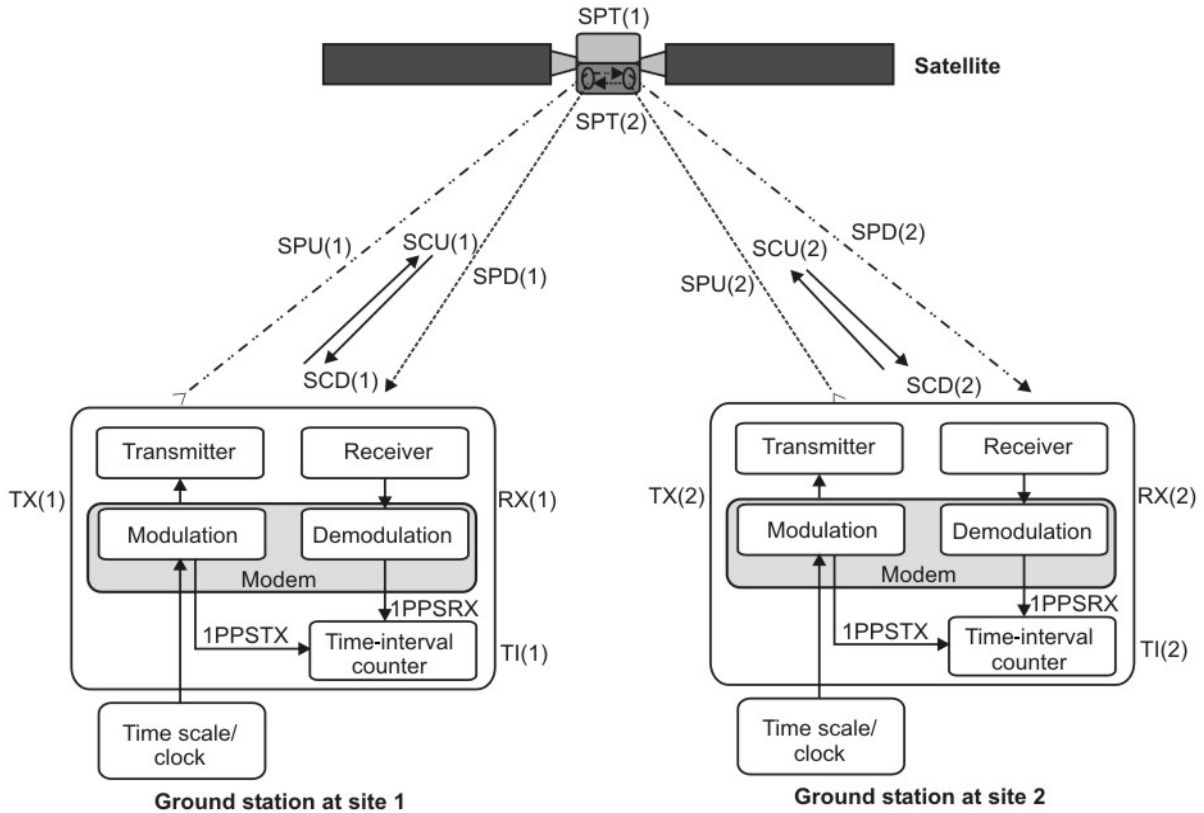
Fig. 1. Schematics of a TWSTFT set-up, including the designation of the various signal delays, as detailed in the list of acronyms.

The difference of the time scale at station 2 from the time scale at station 1, TS(1) – TS(2), is determined as follows:

The TIC reading at station 1 is:

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

and that at station 2 is:

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

Thus

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

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

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

where the last seven terms are corrections for non-reciprocity. Apart from 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.

3.2   Performance characteristics of the ground stations

There are two levels of Earth station performance and operation that must be considered for two-way time transfer. The first level concerns meeting the basic requirements of the modem to produce the desired output phase modulation in the pre-determined schedule, the appropriate transmission frequency, and power level. The second level concerns the performance characteristics of the Earth station as required by the regulatory organizations and satellite-operating agencies.

Meeting regulatory requirements does not in itself guarantee satisfactory two-way operation. Only when the required carrier-to-noise density (C/N_0) and carrier power level (P) is delivered to the modem will one get satisfactory results. Operating parameters are determined from a "link budget", from which one can determine the size of antenna required, the transmittance power required, and the required noise temperature of the receive system. The link budget may be calculated following the direction and examples given in [4].

Regulatory requirements usually originate with the administrative bodies responsible for the general management of the electromagnetic spectrum at national and international level and with the satellite operator. They often dictate when and where an Earth station may be erected, the quality of that Earth station, and its ownership and operation. These rules and regulations are generally intended to guarantee that the Earth station will not generate interference that will affect other Earth stations or adjacent satellites. The issues involved usually include antenna patterns and antenna gain, merit factor (G/T), equivalent isotropically radiated power (EIRP), polarization discrimination criteria, and the training and licensing of operating staff. Most of the technical issues concerned with the Earth station can be guaranteed by the procurement of systems from manufacturers whose equipment has already been approved for operation with specific satellite systems and standards.

Several documents have been identified to provide electrical performance standards, emanating from ITU-R SG4 [5], from the leading satellite operating agency Intelsat [6], and from the US Federal Communications Council (US FCC) [7]. Some regions of the world may have other requirements concerning the satellite system, location, or other criteria.

3.3 Causes of non-reciprocity and systematic uncertainty in TWSTFT

3.3.1 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 XPNDR(1)), should be measured before the launch of the satellite or using another accurate method.

3.3.2 Sagnac-effect correction

Due to the movement of both the Earth stations and the satellite around the rotational 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 with sufficient accuracy by the following model:

$SCD(k) = (\Omega / c^2) [Y(k) X(s) – X(k) Y(s)]$, where:

Ω: Earth rotation rate $= 7.2921 \ 10^{-5}$ rad/s

c: Speed of light $= 299\,792\,458$ m/s

$X(k)$: Geocentric x-coordinate of station
$= (r + HT(k)) \cos[LA(k)] \cos[LO(k)]$

$X(s)$: Geocentric x-coordinate of satellite
$= R \cos[LA(s)] \cos[LO(s)]$

$Y(k)$: Geocentric y-coordinate of station
$= (r + HT(k)) \cos[LA(k)] \sin[LO(k)]$

$Y(s)$: Geocentric y-coordinate of satellite
$= R \cos[LA(s)] \sin[LO(s)]$

r: Earth radius $= 6\,378\,140$ m

R: Satellite orbit radius $= 42\,164\,000$ m

LA: Latitude

LO: Longitude

HT: Height of the station.

For geostationary satellites $LA(s) = 0$, so:
$$SCD(k) = (\Omega / c^2) \ R \ (r + HT(k)) \cos[LA(k)] \sin[LO(k) – LO(s)].$$

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, due to the opposite propagation directions of the signals, the sign of the Sagnac correction for the downlink is opposite to that for the uplink (SCU(k) = – SCD(k)).

Therefore $\qquad$ SCT(1,2) = – SCD(1) + SCD(2).

Example for a satellite at 317° E:

LA(VSL) = 52° N, LO(VSL) = 4° E, LO(s) = 317° E, difference in LO = 47°, HT(VSL) = 76.8 m, SCD(VSL) = +98.90 ns

LA(USNO) = 39° N, LO(USNO) = 283° E, LO(s) = 317° E, difference in LO = –34°, HT(USNO) = 46.9 m, SCD(USNO) = –95.09 ns

SCT(VSL→USNO): –SCD(VSL) + SCD(USNO) = –193.99 ns

SCT(USNO→VSL): –SCD(USNO) + SCD(VSL) = +193.99 ns

VSL: VSL, Delft, the Netherlands
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 picoseconds depending on the location of the participating stations. This has in general been ignored up to now, but needs to be accounted for if particularly high accuracy is required.

3.3.3   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 <u>and</u> 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 picoseconds and shows a diurnal pattern.

3.3.4   Ionospheric correction

The uplink and downlink signals at each station differ in carrier frequency and experience different ionospheric delays given by:

$$40.3 \text{ m}^3/\text{s}^2 \text{ TEC } (1/c) \ (1/f_d^2 - 1/f_u^2)$$

where:

TEC: Total Electron Content along the signal path (unit: 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 $1 \times 10^{18} \text{ m}^{-2}$ and for f_u = 14.5 GHz and f_d = 12.5 GHz the difference between the ionospheric delays is 0.859 ns – 0.639 ns = 0.220 ns. In this case, and in general, the difference 0.5 [SPU(k) – SPD(k)] is thus smaller than 0.11 ns.

3.3.5   Tropospheric correction

The troposphere causes a delay that depends on the elevation angle, the water content of the air, and the air density and temperature; up to 20 GHz this delay is frequency dependent only to a very small

extent. Its influence on the difference between the up and down propagation delays is less than 10 ps.

3.3.6 Earth station delay measurement

The difference of the transmit and receive section [TX(k) – RX(k)], due to components such as the up and down converters, modulator and demodulator (modem), amplifiers, antenna, and cabling, has to be determined at each station. Methods to obtain this are:

– co-location of both stations; or

– subsequent co-location of a third (transportable) Earth station at both stations; or

– the use of a calibrator, e.g. a satellite simulator in conjunction with a calibrated cable.

Calibrations using a transportable station have found wide applications in the time and frequency community. Here it is assumed that the internal delays of the travelling station are unchanged irrespective of the location at which it is installed.

The third method is the least expensive and can in principle be used frequently. This method consists of the calibration of an auxiliary cable, measurement of the sum of the transmit and receive delay, measurement of the sum of the auxiliary cable delay and the receive delay, and calculation of the receive and transmit delay from the measurements.

The internal transmit and receive delay difference of the modem also has to be determined. This can be done by one of the following two methods:

– collocate the two modems of a TWSTFT link and measure the sum of the transmit delay of one modem and the receive delay of the other; or

– measure the sum of the transmit and receive delays of each of the modems in the IF loopback, and use an oscilloscope to measure the transmit delay defined as the phase difference between the 1PPSTX and the transmitter IF output signal. The receive delay is found by subtracting the transmit delay from the measured sum of the delays.

3.4 Combination of TWSTFT measurement data with local measurements

In order to enable the calculation of time-scale differences, each station makes available to the other stations its TI(k) data together with the assessment of its own corrections. One option is the report of the raw 1-s data collected during a particular session in conjunction with a report of the measured local offsets between the various signals involved. The other option, which has become common practice, is to generate a single averaged data point, representative of the session, and only to process this. Independent thereof, one must carefully measure and document the delays which occur in the timing chain of each laboratory. In many cases, the time scales to be compared will ultimately be the local realization of Coordinated Universal Time in each laboratory k UTC(k), but the method is of course amenable for comparisons of time scales in general, such as for the synchronization of the various elements in the ground segment of a Global Navigation Satellite System. Throughout this report we refer to the situation where the stations involved each realize a UTC(k) time scale.

In general, there is an offset between UTC(k) and the physical signal involved in the measurement process, 1PPSTX(k), representing TS(k). The difference UTC(k) − 1PPSTX(k) is in the simplest form reported as the reference delay REFDELAY(k).

The way UTC(k) is realized differs considerably between institutes. In some laboratories UTC(k) is a mathematical time scale. All laboratories, however, have a (master) clock (CLOCK(k)) which is a

physical representation of this time scale. Each laboratory determines the relationship $[UTC(k) - CLOCK(k)]$, either by measurement or by computation. $CLOCK(k)$ can be used as input $1PPSREF(k)$ to the modem. There will probably be an offset $[CLOCK(k) - 1PPSREF(k)]$ caused by the cabling associated with the connection to the modem. The modem generates a $1PPSTX$ which is related to the transmitted signal which allows the difference $[1PPSREF(k) - 1PPSTX(k)]$ to be measured.

The difference between the UTC time scales of the two laboratories can be calculated from the following:

$$
\begin{aligned}
UTC(1) - UTC(2) = \quad & TS(1) - TS(2) \\
& + \{[UTC(1) - CLOCK(1)] \\
& + [CLOCK(1) - 1PPSREF(1)] \\
& + [1PPSREF(1) - 1PPSTX(1)]\} \\
& - \{[UTC(2) - CLOCK(2)] \\
& + [CLOCK(2) - 1PPSREF(2)] \\
& + [1PPSREF(2) - 1PPSTX(2)]\},
\end{aligned}
$$

where the terms in curled brackets are usually abbreviated by $REFDELAY(k)$ as introduced before. Deviations from this procedure have occasionally been used, but are not dealt with here.

4 Book-keeping in a TWSTFT network

4.1 Station identification and assigned characters, codes and offset frequencies

Participating laboratories or institutions are each identified by an identification string (e.g., LAB), preferably that assigned by the BIPM if applicable, and an ASCII character. All stations operate nominally at the same transmit frequency and are distinguished by a unique PRN code (Code Division Multiple Access, CDMA). A clean carrier offset frequency is also assigned, which is needed when all stations of a network transmit a clean carrier (unmodulated) signal. Such a transmission is part of the operational practice to adjust the receive frequency at the remote station, to monitor the power levels in use, and to allow unambiguous identification of the transmitting stations at a given time. If one laboratory routinely operates more than one TWSTFT ground station, each one should have a unique set of identifying parameters, including the station code (e.g. LAB01, LAB02 etc.).

4.2 Session parameters

In this report, the term "session" is used to mean a contiguous period of time during which TWSTFT signals are exchanged between two ground stations. A session is characterized by the following information:

–   satellite identification: name, longitude, orbital parameters, transponder channel, transponder bandwidth, satellite equipment non-reciprocity (if known);
–   ground station designations;
–   link budget;
–   ground station TX and RX frequencies;
–   modem parameters: type of modem, TX and RX codes, chip rate;

–   TX filter type and bandwidth (if applicable)

–   point of contact at each station;

–   start date and time;

–   preparation time for the session (equal to the pause between successive sessions);

–   duration of the session.

In the reported data, the sequence of collected data points is referred to as as "track", and thus one speaks of the nominal and actual track length, etc..

4.3   Local ground station parameters

Each laboratory should keep on file the following information:

–   antenna coordinates (x, y, z in the IERS terrestrial reference frame);

–   ground station designator;

–   transmit power (dBm), or EIRP (dBW);

– G/T of the receiver (dB/K);

–   nominal C/N_0 at the receiver (dBHz);

–   modem: manufacturer, model, type, serial number;

–   antenna: manufacturer, type, diameter, gain;

–   delay calibration: date, method, results;

–   time interval counter: manufacturer, type, serial number, if this is constitutional part of the generation of the TWSTFT measurement results;

–   optional: other data recorded during the sessions such as the measured $TX(k) - RX(k)$ delay, the received power, C/N_0 and frequency, and the environmental parameters at the antenna (temperature, humidity, barometric pressure, weather conditions).

Any change in station parameters and equipment should be reported to the network administrator.

5   Calculation of clock differences

5.1   Calibration of station delays

Calibration of the signal delays in the laboratory's equipment is essential for performing accurate time transfer. Without it one can still perform frequency transfer, assuming stability of the (unknown) delays. TWSTFT links have mostly been calibrated by using a portable TWSTFT station, and an uncertainty of about 1 ns has usually been found. Another possibility is the calibration of a TWSTFT link by using an independent time transfer system, such as GPS, or a portable clock. In principle one can distinguish between calibrations of a link - involving two stations - and of individual signal delays in a particular station.

In order to document the calibration results (CALR) unambiguously in the TWSTFT data files (see Section 6), each calibration is characterized by its type (TYPE), its calibration identifier (CI), and the calibration result (CALR).

The type of calibration technique used for a certain link is described by one of the following:

PORT ES REL	Portable Earth station used in relative mode
PORT ES ABS	Portable Eearth station used in absolute mode
PORT SS REL	Portable satellite simulator used in relative mode
PORT SS ABS	Portable satellite simulator used in absolute mode
GPS	Global Positioning System
PORT CLOCK	Portable clock
CIRCULAR T	Monthly bulletin of the BIPM reporting the difference between UTC and the local realizations UTC(k)
TRIANGLE CLOSURE	Calibration of a link by making use of the calibration results of the links connecting the two stations involved to a third station
CAL *nnn* BRIDGED	When a previous calibration value CAL *nnn* becomes *a priori* obsolete because of changes to the ground or space equipment, it can be carried forward by employing suitable bridging procedures, such as continuous operation of an independent time transfer link in parallel before and after the changes followed by the determination of the delay changes due to the equipment change.

The other parameters are:

CALR	Calibration result in ns. Its use in calculating time scale differences is explained in Sections 5.3 and 5.4.
CI	The assignment of a calibration identification is coordinated by the CCTF Working Group on TWSTFT for the laboratories involved in a specific calibration campaign. Using an independent time-transfer system (e.g. GPS), a calibration is only possible between a pair of laboratories, therefore calibration identifications have to be assigned for pairs of laboratories.
	In the data files (see Section 6 and Annex, examples 2 and 3), the calibration identifier CI is used as a pointer to the file header, which gives information about the calibration type, the Modified Julian Day of the first day of data collection at a particular site during the calibration, and the estimated uncertainty of the calibration. The data files should only contain the currently relevant calibration entries.
	Uncalibrated links can get the indication "999", and there should be no entry of the link in the header of the file reporting the data.
	If a link is re-established after an interruption, but the knowledge of a previous calibration is carried forward by other means ("bridging") with some uncertainty, then a new CI shall be used and TYPE shall indicate the previous CI and the fact of bridging.
ESDVAR(k)	Earth station delay variation (ns), with respect to the Earth station delay at the time of calibration (if available). All Earth station and modem delay changes should be included.
	For each TWSTFT network it has to be decided whether or not the ESDVAR should be reset to zero after calibration of the delays.

5.2 Different data types and calibration procedures

More than one type of modem can be used for TWSTFT, and depending on the modem and its configuration, TWSTFT results can be reported in two different ways:

– individual data: each station reports its own measurement results without any knowledge of measurements results obtained at the remote site; or

– 	combined data: the measurement results obtained at stations 1 and 2 are combined before they are reported, such that the reported "Results" represent the differences between the two measurement results. Particular coordination within the network and the users of the data is required when this option is to be applied.

In data lines, a single-digit "switch" S is used to distinguish between types of calibration, and also between types of reported measurement data.

S 	The switch S (either "0", "1", "2", "5", "6", or "9") indicates the type of data being reported, which terms of the two-way equation (Section 2) are included in the calibration result CALR, and which equation should therefore be used for the computation of the clock differences.

$S = 0$ 	The calibration result CALR gives the difference between the differential Earth station delay (transmit part minus receive part) of the laboratory and the differential Earth station delay of the calibrating system (collocation of Earth stations, satellite simulator). In consequence, the CALR value is specific for each site.

$S = 1$ 	The calibration result CALR includes all terms of the two-way equation except the time transfer measurements TI and the reference measurements REFDELAY of the local and remote station, respectively. This is the case when CALR was obtained using an independent time-transfer system, e.g. GPS. In consequence, the CALR value is specific for each link, and in particular $CALR(i,k) = - CALR(k,i)$.

$S = 2$ 	The calibration result CALR contains the delays of ranging measurements.

$S = 5$ 	The CALR and REFDELAY give the calibration result and reference measurement for the local station in the same way as $S = 1$. However, the differences of the two TWSTFT measurements are reported in the data line. This allows combined data to be reported in two files, but at the same time the unique format of data files supports automated data reduction.

$S = 6$ 	The results CALR and REFDELAY are the combined measurement data from the local and remote stations, and they are reported only in one line in the data file of one station.

$S = 9$ 	The calibration result CALR is either not available or out of date for the individual data reported.

Further information about $S = 5$ and $S = 6$ is given in Section 9.3.

The following subsections explain how clock differences should be determined from the reported data from two stations, depending on the value of S. Reference is made to lines in the data files which are explained in the Annex. Knowledge of the positions of the Earth stations and the satellite allows one to calculate the Sagnac correction (Section 3.3.2) and knowledge of the TEC and the transmit and receive frequencies allows one to calculate the propagation delay due to the ionosphere (Section 3.3.4).

In the cases $S = 0$, $S = 1$ and $S = 9$, the reported data can be the raw 1-s measurement data $TI(k)$ collected during a session. However it is more common for the data to be reported as $TW(k)$ being the result of a quadratic fit over the data collected during the session. In this case $TW(k)$ has to be calculated following a strict and unique rule, otherwise the periodic movement of the satellite causes a variation in the time comparison data which is not real. The rule is that the average data point is calculated for the point in time given by the nominal start date of the session plus half the nominal track length (nominal session duration) rounded to seconds. This rule assumes that the $TI(k)$ data represent instantaneous time interval measurements made at the epoch given by the associated time stamp. If a modem outputs $TI(k)$ as an average over consecutive time interval measurements taken over an interval dT (e.g. 1 s), then the representative data point $TW(k)$ has to

be calculated for the correct nominal epoch. When the modem attributes a measurement value to an epoch T_modem (see example in Section 6.2), then the true epoch is given by T_true = T_modem + dT/2. The value of dT is known to depend on the make of the modem. When reporting 1-s data, it is proposed to report dT/2 in the header of the data file, see Section 6.2.

In the following two subsections, the equations of relevance for the calculation of time scales are elaborated.

5.3 Individual data

$S = 0$:

UTC(1) – UTC(2) =	+ 0.5 [TW(1) + ESDVAR(1)] + REFDELAY(1)	Data line lab 1
	– 0.5 [TW(2) + ESDVAR(2)] – REFDELAY(2)	Data line lab 2
	+ [SCD(2) – SCD(1)]	Header lines lab 1 and lab 2
	+ 0.5 [SPU(1) – SPD(1)]	Header line lab 1
	– 0.5 [SPU(2) – SPD(2)]	Header line lab 2
	+ 0.5 [CALR(1) – CALR(2)]	Data lines lab 1 and lab 2
	+ 0.5 XPNDR(1)	Header line lab 1.

$S = 1$:

UTC(1) – UTC(2) =	+ 0.5 [TW(1) + ESDVAR(1)] + REFDELAY(1)	Data line lab 1
	– 0.5 [TW(2) + ESDVAR(2)] – REFDELAY(2)	Data line lab 2
	+ 0.5 [CALR(1,2) – CALR(2,1)]	Data lines lab 1 and lab 2.

$S = 2$: Determination of the range to the satellite:

RNG(k) =   + 0.5 c [TW(k) – CALR(k) – ESDVAR(k)].

Here c represents the signal propagation speed along the signal path from the satellite to the ground station.

$S = 9$:

UTC(1) – UTC(2) + K =	+ 0.5 [TW(1) + ESDVAR(1)] + REFDELAY(1)	Data line lab 1
	– 0.5 [TW(2) + ESDVAR(2)] – REFDELAY(2)	Data line lab 2.

When no calibration was performed, the time scale difference is known only with an unknown offset K. Note that all above relations remain valid if TW(k) is replaced by TI(k).

5.4 Combined data

To allow the data formats described here also to be used for time scale comparisons, two special cases for the reporting of so-called combined data are introduced in this report. Possible applications emerge if a single operator is responsible for reporting the results of a whole network of stations, or if modem technology allows direct access to the time transfer results obtained at the remote site by real-time data exchange, either over the internet or by low-rate coding of data onto the transmitted RF signals. First we introduce the so-called "clock difference" TW(1,2) which is either equal to 0.5 [TW(1) – TW(2)], or based on individual TI(k) measurements. In the latter case TW(1,2) is the mean of the single differences 0.5 [TI(1) – TI(2)] recorded during one session.

If both stations of a pair report in their data files their local measurements ESDVAR(k), REFDELAY(k) and CALR(k), but use the TW(1,2) output of the modem instead of using the TI(k)

measurements made once per second at each site, the equation below is valid. It has the same mathematical structure as for the $S = 1$ case.

$S = 5$:
$$UTC(1) - UTC(2) = + 0.5 [TW(1,2) + ESDVAR(1)] + REFDELAY(1) \quad \text{Data line lab 1}$$
$$- 0.5 [TW(2,1) + ESDVAR(2)] - REFDELAY(2) \quad \text{Data line lab 2}$$
$$+ 0.5 [CALR(1,2) - CALR(2,1)] \quad \text{Data lines lab 1 and lab 2.}$$

If a single operator takes responsibility for reporting data from the whole network, $S = 6$ can be used. Here, the operator has to compute all quantities from the participating stations.

$S = 6$:
$$UTC(1) - UTC(2) = \quad TW(1,2) + 0.5\,ESDVAR(1,2) + REFDELAY(1,2) + CALR(1,2).$$

In this special case the data are reported in a file originating from station 1 only. Here $TW(1,2)$ is the above-defined clock offset, and the other quantities represent the differences of the respective quantities from those stations (station 1 minus station 2). Thus, $ESDVAR(1,2)$, $REFDELAY(1,2)$, and $CALR(1,2)$ each contain the combined local measurement results. This is referred to again in examples 4 and 5 in the Annex. No file originating from station 2 is needed to compute the time scale difference.

In the case of combined data, uncalibrated results are indicated only by $CI = 999$ and the corresponding entry $CALR = 999999999$. Switch $S = 9$ is reserved for the reporting of individual data.

6 Description of the data format for data exchange

6.1 Definition of file structure, symbols and designations

The TWSTFT data file begins with a header which contains all data that are considered not to change during the period covered by the file (This might be 2 minutes, see Section 6.2, or one day, see Section 6.3). The subsequent data lines contain the data that are expected to change. In the case of individual data, a further distinction is made as to whether the data are the individual 1-s data or the result of a quadratic fit to the 1-s data collected during the session.

The conventions and symbols reported subsequently apply completely to the data format described in Section 6.2 and partly to that in Section 6.3.

LAB: laboratory identification (preferably that assigned by the BIPM or otherwise by the network administrator), four characters maximum
jjjjj: modified Julian day number
hh: UTC hour
mm: UTC minute
ss: UTC second
L: designation of local laboratory by an ASCII character (lower case or capital)
R: designation of remote laboratory by an ASCII character (lower case or capital)
*: indication of the start of a line of text
+: indication of the sign of the subsequent value, either "+" or blank for a positive value, and "−" for a negative value
n: placeholder for a numerical character between 0 and 9
[ ]: designation of an option

n.nnnnnnnnnnnn: value of a time interval (s) (12 decimals, corresponding to 1 ps resolution).

The individual measurement values are typically between 0.250 s and 0.280 s.

6.2   Reporting of individual 1-s measurements

The data file contains a header followed immediately by the lines of data. For ease of implementation, character counters have been added in the field descriptions below which are not to become part of the files.

DATA FILE NAME:
Ljjjjjhh.mmR
where jjjjj, hh, mm give the NOMINAL start date and time of the TWSTFT session.

HEADER:
```
          1         2         3         4         5         6
123456789012345678901234567890123456789012345678901234567890
* Ljjjjjhh.mmR
* UTC(LAB) - CLOCK   = +n.nnnnnnnnnnnn [jjjjj hhmmss]
* CLOCK - 1PPSREF    = +n.nnnnnnnnnnnn [jjjjj hhmmss]
* 1PPSREF - 1PPSTX   = +n.nnnnnnnnnnnn [jjjjj hhmmss]
* dT/2               = +n.nnn [s]
```

Operational parameters can be reported in the following format using as many lines as wished:
```
* PARAMETER = Value [units] [jjjjj hhmmss]
```
where jjjjj, hhmmss optionally give the date at which the indicated value is taken. Note that neither the format nor the contents for the report of parameters are standardized. The header closes with the line
```
* DATA = [1PPSTX - 1PPSRX] | [1PPSREF - 1PPSRX] | [..],
```
as applicable.

DATA:
```
          1         2         3
123456789012345678901234567890
jjjjj hhmmss n.nnnnnnnnnnnn
jjjjj hhmmss n.nnnnnnnnnnnn
```

where jjjjj, hhmmss give the date and time at which the data were recorded.

EXAMPLE:
File C5483108.25E (data measured at station C during a TWSTFT session with station E on MJD 54831, scheduled at 08:25 h UTC):

```
* C5483108.25E
* UTC(VSL) - CLOCK = +0.000000000000  54634  074000
* CLOCK - 1PPSREF  = +0.000000033938  54642  070500
* 1PPSREF - 1PPSTX = +0.000000674202  54831  082446
* dT/2             = +0.500 [s]
* SIGNAL POWER = -51.4 dBm
* SIGNAL C/N0 = 54.5 dBHz
* RX FREQUENCY = 70.0001691 MHz
* JITTER = 0.000000000329 s
* DATA = 1PPSTX - 1PPSRX
54831 082507 0.26751435044
54831 082508 0.26751434770
54831 082509 0.26751434500
54831 082510 0.26751434210
54831 082511 0.26751433944
54831 082512 0.26751433754
54831 082513 0.26751433476
54831 082514 0.26751433152
54831 082515 0.26751432904
54831 082516 0.26751432635
54831 082517 0.26751432370
54831 082518 0.26751432093
54831 082519 0.26751431805
```

Note that in this example the first data line was not generated until 08:25:07 h UTC, which may happen if the modem fails to lock to the received signal during the first seconds of the session.

6.3 Reporting of results of a quadratic fit

6.3.1 General remarks

The purpose of this format is to reduce the amount of data to be exchanged and to be able to report in one data file session results of one laboratory involving different partner stations and different satellite links. Data from more than one day may be reported in a single file. Such files allow clock differences to be calculated in an easy way, using the information given in the header and data lines, without having to know the individual measurement setups at the participating laboratories.

As above there are two kinds of lines:
– lines with an asterisk in column one (file header, data line header);
– lines without an asterisk in column one (data lines).

In the format description below, characters in bold letters indicate the positions of keywords, and characters in italic letters have to be replaced by actual strings or values, respectively (There are no italic or bold characters in the actual data files). Strings in brackets are optional, and whenever data must be preceded by a sign, this is indicated by a "+". Any missing data should be replaced by a series of "9"s covering the full length of the respective data field, including the field reserved for the sign and the decimal point.

Examples in the Annex illustrate the format described below.

6.3.2 File name

The file name consists of **TW**, the designation of the laboratory (laboratory identification *LLLL*, up to four characters) and the Modified Julian Day as given in the first data line (with the last three digits as file extension): **TW***LLLLMM.MMM* (for example TWTUG50.091). The same rule applies if data from more than one day are reported in one file. In the case that two or more Earth stations are operated at one laboratory, the data can still be reported in a single file, as each data line unambiguously refers to those stations in use. However, it may be more convenient to report an individual file for each station. In this case the *LLLL* in the file name should allow distinction between the stations used, e.g. PTB1 and PTB2, or USNO and USNP, etc., as agreed with the network book-keeper.

6.3.3 Header

The number of characters in each header line is limited to 78.

```
.........1.........2.........3.........4.........5.........6.........7........
12345678901234567890123456789012345678901234567890123456789012345678901234567 8
* TWLLLLMM.MMM
* FORMAT     nn
* LAB        LLLL
* REV DATE   YYYY-MM-DD
* ES LLLLnn LA: D dd mm ss.sss       LO: D ddd mm ss.sss    HT: +nnnn.nn m
* REF-FRAME RRRRRRRRRR
* LINK    LL SAT: SSSSSSSSSSSSSSSSSS  NLO: D ddd mm ss.sss  XPNDR: +nnnn.nnn ns
*           SAT-NTX: fffff.ffff MHz  SAT-NRX: fffff.ffff MHz  BW: fff.f MHz
* CAL    CCC TYPE: TTTTTTTTTTTTTTTTT  MJD: MMMMM  EST. UNCERT.: nnnn.nnn ns
* LOC-MON    [YES] [NO]
* MODEM      TYPE, SERIAL NUMBER
* COMMENTS   SSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSS
*
```

TW*LLLLMM.MMM*	File name (see Section 6.3.2)
FORMAT	Format version (between 01 and 99).
LAB	Laboratory identification, preferably that assigned by the BIPM or otherwise by the network administrator.
REV DATE	Revision date of the header data *YYYY-MM-DD* for year, month and day, updated when any parameter specified in the header is changed (other than the file name). Each file from a laboratory must have a unique file name but different files may contain the same header information.
ES	Name and position of Earth station:

LLLLnn Name of Earth station, formed from the laboratory's acronym (up to four characters) and a station identification number (two digits), for example TUG01.

LA Latitude in geodetic coordinates, replacing *D* by N (North) or S (South).

LO Longitude in geodetic coordinates, replacing *D* by W (West) or E (East).

HT Height (m).

One line is used to describe one Earth station, but as many ES lines as necessary can be used.

REF-FRAME Designation of the reference frame of the two-way antenna coordinates. As many characters can be used as necessary (up to 78).

LINK		Information characterizing the satellite links, with the following key details:
	LL	Link identification contained in each data line (data line header: LI, see Section 6.3.4), which points to a specific LINK line of the file header.
	SAT	Satellite identification according to the designation of the satellite-operating agency.
	NLO	Nominal longitude of satellite, replacing *D* by W (West) or E (East).
	XPNDR	Differential transponder delay (ns) (local station to remote station minus remote station to local station).
	SAT-NTX	Nominal transmit frequency of the satellite (MHz), corresponding to the receive frequency of the local Earth station.
	SAT-NRX	Nominal receive frequency of the satellite (MHz), corresponding to the transmit frequency of the local Earth station.
	BW	Frequency bandwidth of the transponder provided by the satellite-operating agency.

Two lines are used to describe each link, but the file can include as many couples of LINK lines as necessary.

CAL		Details of the calibration, with the following information:
	CCC	Calibration identification contained in each data line (data line header: CI, see Section 6.3.4), which points to a specific CAL line of the file header.
	TYPE	Type of technique used for a certain link characterized by one of the key words as described in Section 5.1.
	MJD	Modified Julian Day of the calibration.
	EST.UNCERT	Combined standard measurement uncertainty of the calibration.

Each calibration is described in a single line, but the file can include as many CAL lines as necessary.

LOC-MON	YES or NO indicates whether a local earth station delay monitoring system is available or not.
MODEM	Type and serial number of the modem used. All modems used during the period of validity of the file should be reported.
COMMENTS	Comment lines in free text format, which can be used for example to report chip rates of the PRN codes and parameters of filters in the TX signal path. As many lines as necessary (up to 78 characters per line) can be used.

The last line of the file header contains an asterisk at column 1 only.

6.3.4 Data lines

For the format of the data lines see Example 1 in the Annex. Data lines specify the following information.

EARTH-STAT	The local (LOC) and remote (REM) Earth stations designated by the respective laboratory's acronym (up to four characters) and a station identification number (two digits), for example TUG01. This field is right-justified.
LI	Link identification is a reference to the file header where information can be found on the specific satellite link. The assignment of link identifications has to be coordinated on an international basis, for example by the CCTF Working Group on TWSTFT.

MJD STTIME	Nominal start date (Modified Julian Day and time (hour, minute, second), referenced to UTC).
NTL	Nominal track length (s) (nominal time of last sample minus nominal time of first sample).
TW	Result (s), of a quadratic fit over the data of one track calculated for the date given by the nominal start date plus half of the nominal track length rounded to seconds (corresponds to TW(k) from Annex 1, Section 9.2).

For the cases of $S = 5$ and $S = 6$, the column headed "TW" contains TW(1,2) values.

DRMS	Root mean square of the residuals to the quadratic fit (ns).
SMP	Number of samples used in the quadratic fit.
ATL	Actual track length (s) (time of last sample minus time of first sample of the quadratic fit).
REFDELAY	Delay of the reference with respect to UTC(LAB) (s), as explained in Section 3.4.

For the case of $S = 6$, the column headed "REFDELAY" corresponds to
REFDELAY(1,2) = REFDELAY(1) – REFDELAY(2).

RSIG	Standard measurement uncertainty of the REFDELAY (ns).
CI	Calibration identification corresponding to the details in the file header.
S	Switch (either "0", "1", "2", "5", "6", or "9").
CALR	Calibration result (ns).

For the cases $S = 1$, 5 and 6, the column headed "CALR" corresponds to CALR(1,2).

ESDVAR	Monitored differential Earth station delay variations (ns).

For the case of $S = 6$, the column headed "ESDVAR" corresponds to
ESDVAR(1,2) = ESDVAR(1) – ESDVAR(2).

ESIG	Standard measurement uncertainty of ESDVAR (ns).
TMP	Outside temperature (°C) at the reporting station.
HUM	Outside relative humidity (%) at the reporting station.
PRES	Air pressure (hPa) at the reporting station.

When combined data are reported with $S = 6$, TMP, HUM, PRES shall not be reported. The respective columns shall be filled with "9"s.

7 References

[1] Kirchner D 1991 Two-Way Time Transfer Via Communication Satellites *Proc. of the IEEE* **79** 983-989

[2] Guinot B and Arias E F 2005 Atomic time-keeping from 1955 to the present *Metrologia* **42** S20-S30

[3] ITU Radiocommunication Sector 2003 The operational use of two-way satellite time and frequency transfer employing PN codes *Recommendation ITU-R TF.1153-2 (Geneva, Switzerland)*

[4] ITU Radiocommunication Sector 2002 *ITU Handbook on Satellite Communications (3rd edition, Geneva, 2002)* Section 2.3, Chapter 2 and Section AN2.1, Annex 2

[5] ITU Radiocommunication Sector, Recommendations ITU-R 524, ITU-R S.580, ITU-R S.725, ITU-R S.726, ITU-R S.728, and ITU-R S.729

[6] Intelsat Corporation, IESS-208, IESS-601, and Operational Requirements, Attachment 3

[7] US Federal Communications Council US FCC regulation 25-209 from the Code of Federal Regulations, Title 47, Parts 20-39

8 Acknowledgements

9   Annex: Examples

Example 1   Data line for reporting individual data, quadratic fit.

```
         0         0         0         0         0         0         0         0         0         1         1         1         1
         1         2         3         4         5         6         7         8         9         0         1         2         3
1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890

* EARTH-STAT  LI  MJD   STTIME NTL         TW         DRMS SMP ATL      REFDELAY     RSIG  CI S    CALR       ESDVAR      ESIG TMP HUM PRES
* LOC    REM              hhmmss  s          s          ns  s    s          s         ns           ns          ns          ns degC  %  mbar
LLLLnn LLLLnn LL MMMMM hhmmss nnn +n.nnnnnnnnnnn n.nnn nnn nnn +n.nnnnnnnnnnn n.nnn CCC i +nnnn.nnn +nnnn.nnn n.nnn +nn nnn nnnn
```

Example 2 and 3:   Sample data files from stations in Europe (2) and the United States (3).

2: TWSTFT file from PTB, MJD 54710 (2008-09-01)

```
* TWPTB54.710
* FORMAT    01
* LAB       PTB
* REV DATE  2008-08-28
* ES  PTB04 LA: N  52 17 49.787     LO: E  10 27 37.966   HT:   143.41 m
* REF-FRAME WGS84
* LINK   10 SAT: INTELSAT 3R        NLO: E 317 00 00.000  XPNDR:     0.000 ns
*            SAT-NTX: 12574.2500 MHz  SAT-NRX: 14072.2500 MHz  BW:   2.5 MHz
* LINK   11 SAT: INTELSAT 3R        NLO: E 317 00 00.000  XPNDR: 999999999 ns
*            SAT-NTX: 12627.0500 MHz  SAT-NRX: 14330.7500 MHz  BW:   2.5 MHz
* CAL   113 TYPE: CIRCULAR T        MJD: 54525  EST. UNCERT.:   5.200 ns
* CAL   114 TYPE: CAL 083 BRIDGED   MJD: 54502  EST. UNCERT.:   2.000 ns
* CAL   115 TYPE: CAL 103 BRIDGED   MJD: 54502  EST. UNCERT.:   1.300 ns
* CAL   116 TYPE: CAL 096 BRIDGED   MJD: 54502  EST. UNCERT.:   1.100 ns
* CAL   117 TYPE: CAL 109 BRIDGED   MJD: 54502  EST. UNCERT.:   1.100 ns
* CAL   118 TYPE: CIRCULAR T        MJD: 54502  EST. UNCERT.:   5.000 ns
* CAL   119 TYPE: CAL 106 BRIDGED   MJD: 54502  EST. UNCERT.:   1.200 ns
* CAL   120 TYPE: CAL 107 BRIDGED   MJD: 54502  EST. UNCERT.:   1.200 ns
* LOC-MON   NO
* MODEM     SATRE 037
* COMMENTS
*
* EARTH-STAT LI  MJD  STTIME NTL      TW         DRMS SMP ATL    REFDELAY      RSIG  CI S    CALR       ESDVAR    ESIG TMP HUM PRES
* LOC    REM            hhmmss  s        s          ns   s         s           ns         ns          ns        ns degC  %  mbar
 PTB04   PTB04 10 54710 000700 119  0.268701755755 0.375 120 119 0.000001981575 0.009 999 9 999999999 999999999 99999  18  61 1002
 PTB04    IT02 10 54710 001300 119  0.266832337354 0.607 120 119 0.000001981520 0.010 116 1   316.100   -0.180 0.100  18  61 1002
 PTB04   ROA01 10 54710 001600 119  0.262320415926 0.448 120 119 0.000001981613 0.016 118 1   288.400   -0.180 0.100  17  62 1002
 PTB04    OP01 10 54710 001900 119  0.266437968645 0.376 120 119 0.000001981576 0.014 115 1  7316.500   -0.180 0.100  17  62 1002
 PTB04   NPL01 10 54710 002200 119  0.266586507349 0.693 120 119 0.000001981630 0.014 999 9 999999999   -0.180 0.100  17  62 1002
 PTB04    CH01 10 54710 003700 119  0.267009789103 0.375 120 119 0.000001981722 0.018 117 1   204.550   -0.180 0.100  17  64 1001
 PTB04   IPQ01 10 54710 004000 119  0.262213386716 0.529 120 119 0.000001981839 0.012 999 9 999999999   -0.180 0.100  17  64 1001
 PTB04   AOS01 10 54710 004300 119  0.270015381981 0.415 120 119 0.000001981716 0.012 999 9 999999999   -0.180 0.100  17  64 1001
 PTB04 USNO01 11 54710 004600 119  0.262319009268 0.224 120 119 0.000001981668 0.009 114 1  -218.800   -0.180 0.100  17  65 1002
 PTB04 NIST01 11 54710 004900 119  0.268893360924 0.225 120 119 0.000001981639 0.013 113 1    30.100   -0.180 0.100  17  65 1002
```

3: TWSTFT file from NIST, MJD 54710 (2008-09-01)

```
* TWNIST54.710
* FORMAT    01
* LAB       NIST
* REV DATE  2008-08-22
* ES NIST01 LA: N  39 59 45.000      LO: W 105 15 46.000   HT: +1640.00 m
* REF-FRAME WGS84
* LINK   11 SAT: INTELSAT 3R        NLO: E 317 00 00.000  XPNDR: 999999999 ns
*          SAT-NTX: 12030.7500 MHz  SAT-NRX: 14375.0500 MHz  BW:   2.5 MHz
* CAL   113 TYPE: CIRCULAR T         MJD: 54525  EST. UNCERT.:    5.200 ns
* CAL   322 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   324 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   326 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   328 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   329 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   330 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   331 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* LOC-MON   NO
* MODEM     SATRE, S/N 78
*
* EARTH-STAT  LI  MJD  STTIME NTL        TW         DRMS SMP ATL     REFDELAY       RSIG  CI S     CALR      ESDVAR    ESIG TMP HUM PRES
* LOC    REM              hhmmss  s        s          ns   s   s        s            ns            ns        ns        ns degC  %  mbar
NIST01  IPQ01 11 54710 001900 119 +0.267703968380 0.141 120 119 +0.000000860500 99999 999 9 999999999 224.040 0.200  24  44  827
NIST01  AOS01 11 54710 002200 119 +0.270196963882 0.422 120 119 +0.000000860500 99999 322 1   154.480 224.040 99999  24  44  827
NIST01   CH01 11 54710 002800 119 +0.267193679499 0.182 120 119 +0.000000860500 99999 324 1   176.060 224.040 99999  24  44  827
NIST01   OP01 11 54710 003700 119 +0.266627169522 0.105 120 119 +0.000000860500 99999 328 1  7287.687 224.040 99999  24  44  827
NIST01  VSL01 11 54710 004300 119 +0.267708090797 0.227 120 119 +0.000000860500 99999 331 1   273.323 224.040 99999  24  44  827
NIST01  PTB04 11 54710 004900 119 +0.268895559344 0.140 120 119 +0.000000860500 99999 113 1   -30.100 224.040 99999  24  44  827
NIST01   IT02 11 54710 005200 119 +0.267025340834 0.233 120 119 +0.000000860500 99999 326 1   285.833 224.040 99999  24  44  827
NIST01  ROA01 11 54710 005500 119 +0.262513121858 0.184 120 119 +0.000000860500 99999 999 9 999999999 224.040 0.200  24  44  827
NIST01  IPQ01 11 54710 021900 119 +0.267722017937 0.092 120 119 +0.000000860500 99999 999 9 999999999 224.040 0.200  21  61  828
NIST01  AOS01 11 54710 022200 119 +0.270215057832 0.294 120 119 +0.000000860500 99999 322 1   154.480 224.040 99999  21  61  828
NIST01   CH01 11 54710 022800 119 +0.267211280933 0.226 120 119 +0.000000860500 99999 324 1   176.060 224.040 99999  21  61  828
NIST01   OP01 11 54710 023700 119 +0.266644173922 0.104 120 119 +0.000000860500 99999 328 1  7287.687 224.040 99999  21  61  828
NIST01  VSL01 11 54710 024300 119 +0.267724824316 0.260 120 119 +0.000000860500 99999 331 1   273.323 224.040 99999  21  61  828
NIST01  PTB04 11 54710 024900 119 +0.268912075975 0.209 120 119 +0.000000860500 99999 113 1   -30.100 224.040 99999  21  61  828
NIST01   IT02 11 54710 025200 119 +0.267041591354 0.246 120 119 +0.000000860500 99999 326 1   285.833 224.040 99999  21  61  828
NIST01  ROA01 11 54710 025500 119 +0.262528556357 0.110 120 119 +0.000000860500 99999 999 9 999999999 224.040 0.200  21  61  828
```

Example 4 and 5:   Sample data files based on examples 2 and 3, but reporting combined data ($S = 5$ and $S = 6$).

4: Modified TWSTFT file from PTB, MJD 54710 (2008-09-14)

```
* twptb54.710
* FORMAT    01
* LAB       PTB
* REV DATE  2008-08-28
* ES  PTB04 LA: N  52 17 49.787     LO: E  10 27 37.966   HT:    143.41 m
* REF-FRAME WGS84
* LINK   10 SAT: INTELSAT 3R        NLO: E 317 00 00.000  XPNDR:     0.000 ns
*           SAT-NTX: 12574.2500 MHz  SAT-NRX: 14072.2500 MHz  BW:   2.5 MHz
* LINK   11 SAT: INTELSAT 3R        NLO: E 317 00 00.000  XPNDR: +9999.999 ns
*           SAT-NTX: 12627.0500 MHz  SAT-NRX: 14330.7500 MHz  BW:   2.5 MHz
* CAL    113 TYPE: CIRCULAR T        MJD: 54525  EST. UNCERT.:    5.200 ns
* CAL    114 TYPE: CAL 083 BRIDGED   MJD: 54502  EST. UNCERT.:    2.000 ns
* CAL    115 TYPE: CAL 103 BRIDGED   MJD: 54502  EST. UNCERT.:    1.300 ns
* CAL    116 TYPE: CAL 096 BRIDGED   MJD: 54502  EST. UNCERT.:    1.100 ns
* CAL    117 TYPE: CAL 109 BRIDGED   MJD: 54502  EST. UNCERT.:    1.100 ns
* CAL    118 TYPE: CIRCULAR T        MJD: 54502  EST. UNCERT.:    5.000 ns
* CAL    119 TYPE: CAL 106 BRIDGED   MJD: 54502  EST. UNCERT.:    1.200 ns
* CAL    120 TYPE: CAL 107 BRIDGED   MJD: 54502  EST. UNCERT.:    1.200 ns
* LOC-MON    NO
* MODEM      SATRE 037
* COMMENTS
*
* EARTH-STAT  LI  MJD  STTIME NTL        TW         DRMS SMP ATL     REFDELAY     RSIG  CI S    CALR      ESDVAR   ESIG TMP HUM PRES
* LOC    REM            hhmmss  s          s          ns   s         s            ns           ns        ns       ns degC  %  mbar
 PTB04  PTB04 10 54710 000700 119  0.268701755755 0.375 120 119 0.000001981575 0.009 999 9 999999999   -0.180 0.100  18  61 1002
 PTB04  NIST01 11 54710 004900 119 -0.000001099210 0.265 120 119 0.000001981639 0.013 113 5    30.100   -0.180 0.100  17  65 1002
 PTB04  NIST01 11 54710 024900 119 -0.000002198420 0.265 120 119 0.000001122251 0.010 113 6    30.100 -224.220 0.100  16  72 1000
```

5 : Modified TWSTFT file from NIST, MJD 54710 (2008-09-01)

```
* TWNIST54.710
* FORMAT    01
* LAB       NIST
* REV DATE  2008-08-22
* ES NIST01 LA: N  39 59 45.000      LO: W 105 15 46.000   HT: +1640.00 m
* REF-FRAME WGS84
* LINK   11 SAT: INTELSAT 3R         NLO: E 317 00 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 12030.7500 MHz  SAT-NRX: 14375.0500 MHz  BW:   2.5 MHz
* CAL   113 TYPE: CIRCULAR T         MJD: 54525  EST. UNCERT.:    5.200 ns
* CAL   322 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   324 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   326 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   328 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   329 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   330 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* CAL   331 TYPE: TRIANGLE CLOSURE   MJD: 54584  EST. UNCERT.:    6.000 ns
* LOC-MON   NO
* MODEM     SATRE, S/N 78
*
* EARTH-STAT  LI  MJD  STTIME NTL        TW         DRMS SMP ATL    REFDELAY      RSIG  CI S    CALR      ESDVAR    ESIG TMP HUM PRES
* LOC    REM              hhmmss  s         s           ns   s       s            ns              ns        ns      ns degC  %  mbar
NIST01 PTB04 11 54710 004900 119 +0.000001099210 0.140 120 119 +0.000000860500 99999 113 5   -30.100    224.040 99999  24  44  827
```