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Recommendation ITU-R TF.1153-3
(03/2010)

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

TF Series

Time signals and frequency standards emissions

International Telecommunication Union

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RECOMMENDATION ITU-R TF.1153-3

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

(Question ITU-R 250/7)

(1995-1997-2003-2010)

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. Operational practice of TWSTFT and the equipment involved have changed considerably since the first and second issue of Recommendation ITU-R TF.1153 were released in 1997 and 2003, respectively. The current version takes care of this.

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.

FIGURE 1

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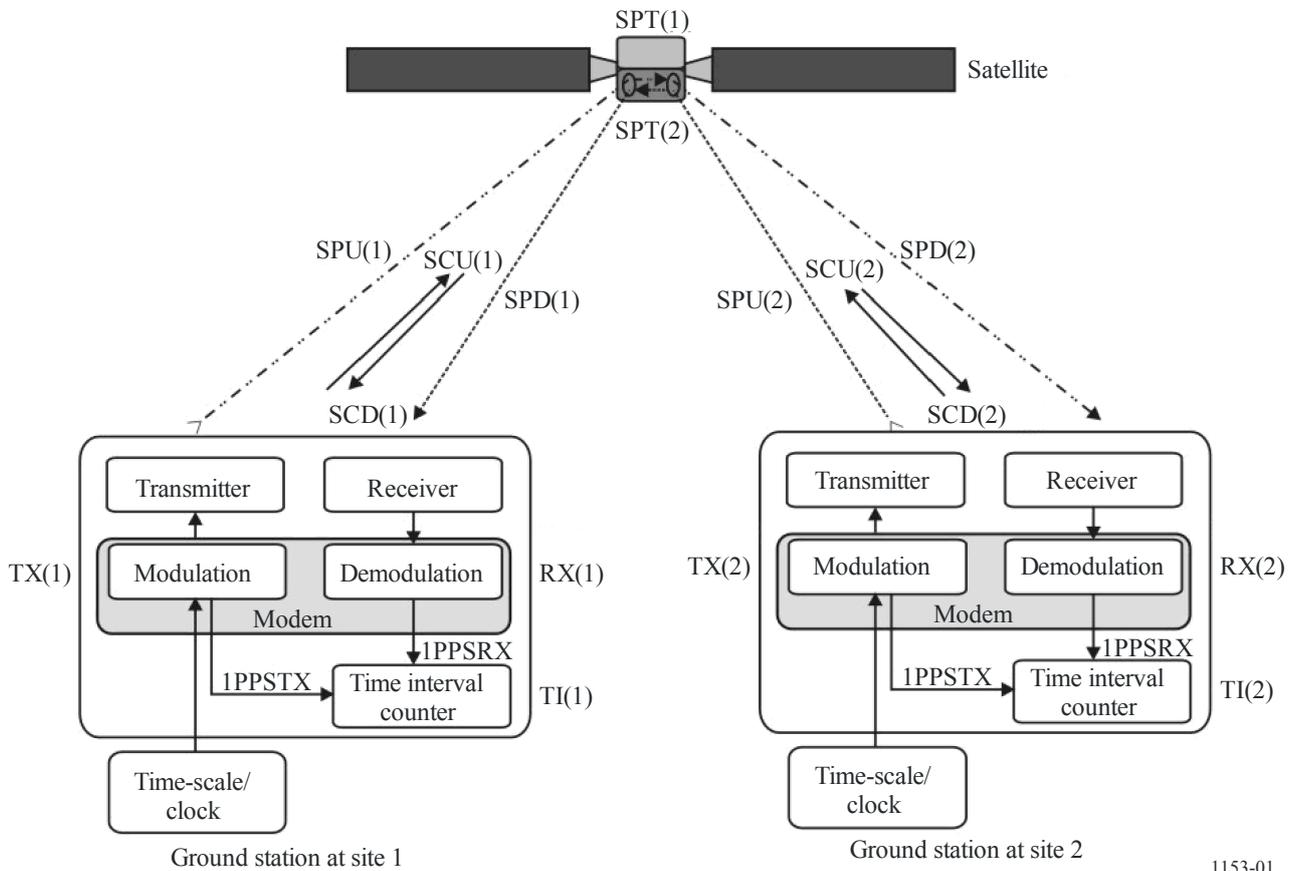
Figure 1 illustrates the various signal delays and explains how the time difference between the clocks at stations 1 and 2 can be determined. The various acronyms have the following significance.

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:

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

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 model which provides sufficient accuracy by:

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

where:

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

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

$X(k)$: Geocentric x-coordinate of station (m)

$\quad = \quad (r + HT(k))\cos[LA(k)]\cos[LO(k)]$

$X(s)$: Geocentric x-coordinate of satellite (m)

$\quad = \quad R\cos[LA(s)]\cos[LO(s)]$

$Y(k)$: Geocentric y-coordinate of station (m)

$\quad = \quad (r + HT(k))\cos[LA(k)]\sin[LO(k)]$

$Y(s)$: Geocentric y-coordinate of satellite (m)

$\quad = \quad R\cos[LA(s)]\sin[LO(s)]$

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, 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 317° E:

LA(VSL) = 52° N, LO(VSL) = 4° E, LO(sat) = 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(sat) = 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: 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 $f_u = 14.5$ GHz and $f_d = 12.5$ 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 ps.

3.6 Earth station delay measurement

The difference of the transmit and receive section [TX(k) − 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:

– co-location of both stations; or

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

– the use of a calibrator, e.g. a satellite-simulator and 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 where it is installed.

The last 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 has to be determined as well. This can be done by the following two methods:

–   Co-locate 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.

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

4   Combination of TWSTFT measurement data with local measurements

In order to enable the calculation of time-scale differences, each station makes available the TI(k) data together with the assessment of its own corrections, as far as possible, to the other stations. 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 (see next paragraph). 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 realizations of Coordinated Universal Time (UTC) in laboratory k, called UTC(k). But the method is of course amenable for comparisons of time-scales in general, e.g. for the synchronization of the various elements in the ground segment of a global navigation satellite system. Throughout this Recommendation we refer to the situation that the two 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 timescale. All laboratories, however, have a (master) clock (CLOCK(k)) which is a physical representation of this timescale. 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 likely 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.

To calculate the difference between the UTC time-scales of the two laboratories from the measured quantities TS(1) and TS(2) (see § 2) the following applies:

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

For abbreviation, the terms in curled brackets are designated REFDELAY(k) as introduced before. Deviations of the aforementioned procedures have been occasionally used, but are not dealt with in this Recommendation.

5   Performance characteristics of the technique

There are two levels of earth station performance and operation that must be considered for two-way time transfers. The first level concerns meeting the basic requirements of the modem to produce the desired output phase modulation in the predetermined 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 do not by themselves 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 this link budget one can determine the size of antenna required, the transmit power required and the required noise temperature of the receive system. The link budget may be calculated following the direction and examples given in § 2.3, Chapter 2 and Section AN2.1, Annex 2 of the ITU Handbook on Satellite Communications (third edition, Geneva, 2002).

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. The rules and regulations 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 usually are intended to guarantee that the earth station will not generate interference to other earth stations and to other adjacent satellites. 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. Much of the technical matter concerned with the earth station can be guaranteed by the procurement of systems from manufacturers who have already qualified the equipment for operation with specific satellite systems and standards.

The following References have been identified to provide electrical performance standards:

From Radiocommunication SG 4: Recommendations ITU-R S.524, ITU-R S.580, ITU-R S.725, ITU-R S.726, ITU-R S.728 and ITU-R S.729.

From the leading satellite operating agency Intelsat: IESS-208, IESS-601, and Operational Requirements, Attachment 3.

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

Some regions of the world may have other requirements relating to the satellite system, location, classification of user, and other criteria.

In determining the accuracy and stability of the results, the general guidelines of the International Organization for Standardization (ISO/IEC Guide 98: 1995) "Guide to the expression of uncertainty in measurement (GUM)" should be followed, along with the characterization of performance procedures outlined in Recommendation ITU-R TF.538.

6   TWSTFT operations in a network

The need for standardizing measuring procedures, data processing, and the formats for the exchange of data and relevant information between participating stations is obvious if a network of stations exists and if the data shall be amenable for automatic processing by the involved institutions and third parties. This Recommendation builds on well-established practice currently in use in the networks comprising timing institutes in Europe and the United States of America, in Europe and Asia, and also within the Asia-Pacific Region, contributing to the realization of UTC. Coordination

of these networks is assured by the CCTF Working Group on TWSTFT. For each of the networks, an administrator is usually assigned as point of contact.

6.1 Station identification and assigned characters, codes and offset-frequencies

Participating laboratories or institutions are each identified by an identification string (e.g. LAB), preferentially that assigned by 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 get a unique set of identifying parameters, including a station code (e.g. LAB01, LAB02, etc.).

6.2 Session parameters

In this annex, the term "session" is used for a contiguous period of time during which TWSTFT signals are exchanged between two ground stations. A session is characterized with 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-codes and RX-codes, chip-rate;

– TX filter type and bandwidth (if applicable);

– start date and time;

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

– duration of the session;

– point of contact at each station.

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

6.3 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;

–   optional: record during the sessions the measured TX(k) − RX(k) delay, received power, the receive C/N_0 and frequency, and the environmental parameters at the antenna (temperature, humidity, barometric pressure, weather conditions);

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

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

7   Calibration of station delays

Calibration of the signal delays in the laboratory's equipment is essential for performing accurate time transfer. Without that one can still perform frequency transfer, assuming sufficient 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 been repeatedly demonstrated. 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 (to be described in Annex 2), each calibration is characterized by its TYPE, by its calibration identifier CI, and by a calibration result CALR.

TYPE   Type of technique used for a certain link characterized by one of the following key words:

PORT ES REL   Portable earth station used in a relative mode.

PORT ES ABS   Portable earth station used in an absolute mode.

PORT SS REL   Portable satellite simulator used in a relative mode.

PORT SS ABS   Portable satellite simulator used in an absolute mode.

Calibration by an independent time transfer system or other means, for example:

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 one 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 of 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.

CALR   Calibration result in ns. Its use in calculating time-scale differences is explained in § 8, Annex 1.

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 Annex 2), the calibration identifier CI is used as a pointer to the file header, which informs about the calibration type, the Modified Julian Day[1] of the first day when data are taken at a respective site during the calibration, and the estimated uncertainty of the calibration. The data files should only contain the currently relevant calibration entries.

Uncalibrated links should get the indication "999", and there should be no entry of the link in the header of the file reporting the data (see Annex 2, § 3.3).

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 designate the old CI and the fact of bridging.

ESDVAR(k)   Earth station delay variation (ns), with respect to the earth station delay present at the time of a calibration – if such a calibration is available. All earth station and modem delay changes have to be included.

For each TWSTFT network it has to be decided whether the ESDVAR is re-set to zero or not when a delay calibration has taken place.

8   Calculation of clock differences

8.1   Introduction

At present there exist more than one type of modem for TWSTFT, and depending on the modem in use and its configuration, TWSTFT results can be reported in two different ways.

Report of individual data: Each station reports its own measurement results without any knowledge of measurement results obtained at the remote site.

Report of combined data: The measurement results obtained at stations 1 and 2 are combined before they are reported. "Results" is the difference of the two measurement results. Particular coordination within the network and the users of the data is required when this option shall be applied.

In data lines, a numerical 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 which type of data are reported, which terms of the two-way equation (§ 2) are included in the calibration result CALR, and which equation must 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.

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[1] Definition of modified Julian date (MJD) is provided in Recommendation ITU-R TF.457.

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(1,2) = −CALR(2,1).

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 time transfer measurements, CALR and REFDELAY are the combined measurement data from the local and the remote station, and they are reported only in one line in the data file of one station.

Explanations regarding S = 5 and S = 6 are given in § 8.3.

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

The following subsections explain how clock differences are to be determined based on the reported data from two stations, in dependence on switch S. Reference is made to lines in the data files which are explained in Annex 2. The knowledge of the positions of the earth stations and the satellite allows one to calculate the Sagnac correction (§ 3.2) and the knowledge of the TEC and the transmit and receive frequencies allows one to calculate the propagation delay due to the ionosphere (§ 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. More common is the report of the result of a quadratic fit over the data collected during one session, designated TW(k). 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 nominal epoch −dT/2. When reporting 1-s data, it is proposed to report dT in the header of the data file, see Annex 2, § 2.

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

8.2   Individual data

S = 0:

$$UTC(1) - UTC(2) = \qquad + 0.5\,[TW(1) + ESDVAR(1)] + REFDELAY(1) \quad \text{Data line lab 1}$$

$$- 0.5\,[TW(2) + ESDVAR(2)] - REFDELAY(2) \quad \text{Data line lab 2}$$

$$+ \,[SCD(2) - SCD(1)] \qquad \qquad \text{Header lines lab 1 and lab 2}$$

$$+ 0.5\,[SPU(1) - SPD(1)] \qquad \qquad \text{Header line lab 1}$$

$$- 0.5\,[SPU(2) - SPD(2)] \qquad \qquad \text{Header line lab 2}$$

$$+ 0.5 \text{ [CALR(1)}$$

$$- \text{CALR(2)]} \qquad\qquad \text{Data lines lab 1 and lab 2}$$

$$+ 0.5 \text{ XPNDR(1)} \qquad\qquad \text{Header line lab 1.}$$

S = 1:

$$\text{UTC(1)} - \text{UTC(2)} = \qquad + 0.5 \text{ [TW(1)} + \text{ESDVAR(1)]} + \text{REFDELAY(1)} \quad \text{Data line lab 1}$$

$$- 0.5 \text{ [TW(2)} + \text{ESDVAR(2)]} - \text{REFDELAY(2)} \quad \text{Data line lab 2}$$

$$+ 0.5 \text{ [CALR(1,2)} - \text{CALR(2,1)]} \qquad \text{Data lines lab 1 and lab 2.}$$

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

$$\text{RNG(k)} = \qquad\qquad 0.5 \, c \text{ [TW(k)} - \text{CALR(k)} - \text{ESDVAR(k)].}$$

Here c has to be understood as the signal propagation speed along the signal path from the satellite to the ground station.

S = 9:

$$\text{UTC(1)} - \text{UTC(2)} + \text{K} = \qquad + 0.5 \text{ [TW(1)} + \text{ESDVAR(1)]} + \text{REFDELAY(1)} \quad \text{Data line lab 1}$$

$$- 0.5 \text{ [TW(2)} + \text{ESDVAR(2)]} - \text{REFDELAY(2)} \quad \text{Data line lab 2.}$$

When no calibration was performed, the time-scale difference is known only with an unknown offset K.

NOTE 1 – All above relations remain valid if TW(k) is replaced by TI(k).

8.3 Combined data

To allow a broader use of the data formats introduced in this Recommendation for time-scale comparisons, two special cases for the so-called report of combined data will be introduced in the following. Possible applications emerge if one operator takes care for reporting the results of a whole network of stations, or if modem technology allows a direct access to 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. At 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 two 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 secondly provided TI(k) measurements at each site, the equation below is valid which has the same mathematical structure as that for the S = 1 case.

S = 5:

$$\text{UTC(1)} - \text{UTC(2)} = \qquad + 0.5 \text{ [TW(1,2)} + \text{ESDVAR(1)]} + \text{REFDELAY(1)} \quad \text{Data line lab 1}$$

$$- 0.5 \text{ [TW(2,1)} + \text{ESDVAR(2)]} - \text{REFDELAY(2)} \quad \text{Data line lab 2}$$

$$+ 0.5 \text{ [CALR(1,2)} - \text{CALR(2,1)]} \qquad \text{Data lines lab 1 and lab 2.}$$

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

S = 6:

$$\text{UTC(1)} - \text{UTC(2)} = \qquad\qquad \text{TW(1,2)} + 0.5 \text{ ESDVAR(1,2)} + \text{REFDELAY(1,2)} + \text{CALR(1,2).}$$

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 respective quantities from station 1 minus station 2. Thus, ESDVAR(1,2), REFDELAY(1,2) and CALR(1,2) contain each the combined local measurement results. This is referred to again in § 3.4 of Annex 2. No file originating from station 2 is needed to compute the time-scale difference.

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

Annex 2

Description of the data format for data exchange

1   Introduction

The data file begins with a header which contains all data that are not considered to change during the period of reporting TWSTFT in one file (e.g. 2 min, see § 2 of Annex 2, or one day, see § 3 of Annex 2). The subsequent data lines contain all data that are expected to change.

The above is valid for individual and combined data as described in Annex 1, § 8.1. In case of individual data, a further distinction is made whether the individual 1-s data are reported 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 § 2 and partly to that in § 3 of Annex 2.

LAB: laboratory identification (preferentially according to the BIPM convention or as assigned by the network administrator), four characters maximum

jjjjj: modified Julian day

hh: UTC hour

mm: UTC minute

ss: UTC second

L: designation of Local laboratory by an ASCII character (small or capital)

R: designation of Remote laboratory by an ASCII character (small 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.

2   Report of the individual 1-s measurements

The data file contains a HEADER followed immediately by DATA lines. For the ease of implementation, rulers 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
1234567890123456789012345678901234567890123456789012345678901234567890
*
* UTC(LAB) - CLOCK = +n.nnnnnnnnnnn [jjjjj hhmmss]
* CLOCK - 1PPSREF  = +n.nnnnnnnnnnn [jjjjj hhmmss]
* 1PPSREF - 1PPSTX = +n.nnnnnnnnnnn [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, as many lines of that kind as deemed necessary. 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
1234567890123456789012345678901234567890
jjjjj hhmmss n.nnnnnnnnnnnn
jjjjj hhmmss n.nnnnnnnnnnnn
```

where jjjjj, hhmmss give the date at which the data is taken.

EXAMPLE:

File C5483108.25E (data measured at station C during a TWSTFT session with station E on MJD 54831, scheduled at 0825 h UTC):

```
* C5483108.25E
* UTC(VSL) - CLOCK = +0.000000000000  54634  074000
* CLOCK - 1PPSREF  = +0.000000033938  54642  070500
* 1PPSREF - 1PPSTX =  0.000000674202  54831  082446
* 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 1 – In this example the first data line is generated only at 08:25:07 UTC, which may happen if the modem fails to lock to the received signal during the first seconds of the session.

3 File format reporting results of a quadratic fit

Examples in § 4 of Annex 2 illustrate the format described subsequently.

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 of more than one day may be reported in one file. It allows clock differences to be calculated in an easy way, using the information given in the header and data lines, without having to know individual measurement set-ups at the participating laboratories.

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

3.2 File name

The file name consists of **TW**, the designation of the laboratory (*LLLL*, laboratory identification, up to four characters) and the Modified Julian Day as given in the first data line (the last three digits as file extension): **TW***LLLLMM.MMM* (for example TWTUG50.091). The same rule shall apply 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 be reported in one file, as each data line unambiguously refers to the 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 shall allow distinction between the stations used, e.g. PTB1 and PTB2, or USNO and USNP, etc., as agreed with the network bookkeeper.

NOTE 1 – Although combined data can be reported in the data lines, the header will only contain information of the local station involved.

3.3 Header

Number of columns in header lines are 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 RRRRRRRRR
*  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: TTTTTTTTTTTTTTTTTT    MJD: MMMMM  EST. UNCERT.: nnnn.nnn ns
*  LOC-MON    [YES] [NO]
*  MODEM      TYPE, SERIAL NUMBER
*  COMMENTS SSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSS
```

TWLLLLMM.MMM	File name (see § 3.2).
FORMAT	Format version (from 01 to 99).
LAB	Laboratory identification, preferentially according to the BIPM convention or as assigned by the network administrator.
REV DATE	Revision date of the header data, changed when one parameter given in the header is changed apart from the file name. Each file of one laboratory has to have a unique file name and different files may have the same header. *YYYY-MM-DD* for year, month and day.
ES	Name and position of earth station:

	LLLLnn	Name of earth station formed of 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 describes 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 columns as necessary.
LINK	LINK lines characterize the satellite links.

	LL	Link identification contained in each data line (data line header: LI, see § 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). This frequency corresponds to the receive frequency of the local earth station.
	SAT-NRX	Nominal receive frequency of the satellite (MHz). This frequency corresponds to the transmit frequency of the local earth station.
	BW	Frequency bandwidth of the transponder provided by the satellite operating agency.

Two lines describe one link, but as many couples of LINK lines as necessary can be used.

CAL   CAL lines give the calibration type, the Modified Julian Day and the combined standard measurement uncertainty of the calibration:

        CCC   Calibration identification contained in each data line (data line header: CI, see § 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 Annex 1 § 9.

        MJD   Modified Julian Day of the calibration.

        EST.UNCERT.   Combined standard measurement uncertainty of the calibration.

A calibration is described in one line, but as many CAL lines as necessary can be used.

LOC-MON   YES or NO has to be used depending on the availability of a local earth station delay monitoring system.

MODEM   Type and serial number of modem used. All modems used during the period of validity of the file should be reported.

COMMENTS   Comment lines − in free text format. This line may be used to report chip rates of the PRN codes and parameters of filters in the TX signal path.

As many lines and columns (up to 78 characters per line) as necessary can be used.

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

3.4   Data line

For the format of a data line see example 1 in § 4 of Annex 2.

EARTH-STAT Designation of local (LOC) and remote (REM) earth station given 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 pointer to the file header that gives information on a specific satellite link.

        The assignment of link identifications has to be coordinated on an international basis such as by the CCTF Working Group on Two-Way Satellite Time and Frequency Transfer.

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, § 9.2).

        In case of S = 5, 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), explained in Annex 1, § 4.

In case of S = 6, the column headed "REFDELAY" contains REFDELAY(1,2) = : REFDELAY(1) – REFDELAY(2) values.

RSIG   Standard measurement uncertainty of the REFDELAY (ns).

CI   Calibration identification is a pointer to the file header.

S   Switch (either "0", "1", "2", "5", "6", or "9").

CALR   Calibration result (ns).

In case of S = 1, 5 and 6, the column headed "CALR" contains CALR(1,2).

ESDVAR   Monitored differential earth station delay variations (ns).

In case of S = 6, the column headed "ESDVAR" contains ESDVAR(1,2) = ESDVAR(1) – ESDVAR(2) values.

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, the last three columns shall be filled with "9"s.

4   Examples

The examples contain actual and fictitious data:

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        ns            ns          ns         ns       ns degC  %  mbar

LLLLnn LLLLnn LL MMMMM hhmmss nnn +n.nnnnnnnnnnnn n.nnn nnn nnn +n.nnnnnnnnnnnn n.nnn CCC i +nnnn.nnn +nnnn.nnn n.nnn +nn nnn nnnn
```

Examples 2 and 3:   Sample data files from a station in Europe (2) and in United States of America (3)

2: TWSTFT file of 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
* LINK   11 SAT: INTELSAT 3R        NLO: E 317 00 00.000  XPNDR: 999999999 ns
*           SAT-NTX: 12627.0500 MHz  SAT-NRX: 14330.7500 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        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 of 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
* 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
```

Examples 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 of PTB, MJD 54710, 2008-09-014

```
* 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
* 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
* 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       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 of 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
* 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  PTB04 11 54710 004900 119 +0.000001099210 0.140 120 119 +0.000000860500 99999 113 5   -30.100    224.040 99999  24  44  827
```