RECOMMENDATION ITU-R TF.1153-1

THE OPERATIONAL USE OF TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER EMPLOYING PN CODES

(Question ITU-R 201/7)

(1995-1997)

The ITU Radiocommunication Assembly,

considering

a) the potential for high-accuracy time and frequency transfer of the two-way satellite method (TWSTFT) as expressed in Question ITU-R 201/7;

b) the demonstrated high performance of TWSTFT systems using telecommunication satellites in the 14/11 and 14/12 GHz bands;

c) that other frequency bands are becoming important;

d) the demonstrated time calibration results of TWSTFT systems;

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 the number of participants is increasing;

g) the need for standardizing:

– measuring procedures,

– data processing,

– format for the exchange of data and relevant information between pairs of participants,

recommends

1 that the measuring and data processing procedures for accurate time and frequency transfer be followed as outlined in Annex 1;

2 that the data format for the exchange of the relevant data between pairs of participants should include the information as outlined in Annex 2.

ANNEX 1

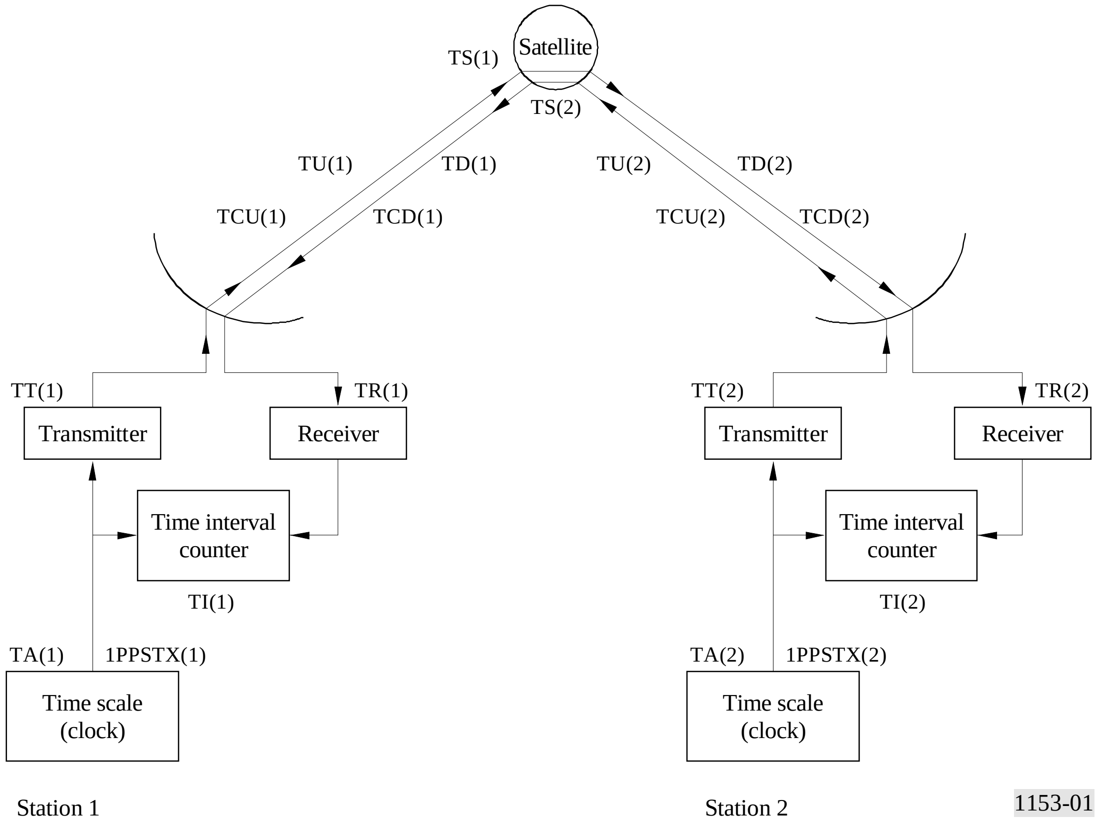
Procedures for TWSTFT

1 Introduction

Radio links can be used to transfer time from one clock to another. 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 the same instant and on both sides the signal from the other clock is received and measured. After the exchange of the measured data, the difference of the two clocks is calculated. The delays cancel due to the complete 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 known and others are still unknown. In some cases corrections for these effects can be used to improve accuracy.

FIGURE 1

TWSTFT principle



From Fig. 1, it can be seen how the difference of the clocks at stations 1 and 2 can be determined.

TA(k): time-scale of the 1PPSTX reference point at station k, k being 1 for station 1 and 2 for station 2

TI(k): time interval reading

TT(k): transmitter delay, including the modem delay

TR(k): receiver delay, including the modem delay

TU(k): uplink propagation delay

TD(k): downlink propagation delay

TS(k): satellite delay

TCU(k): Sagnac correction in the uplink

TCD(k): Sagnac correction in the downlink.

The difference of the time-scale (1PPSTX) at station 2 from the time-scale (1PPSTX) at station 1 expressed by TA(1) − TA(2) is determined as follows.

The time interval counter (TIC) reading at station 1 is:

$$TI(1) = TA(1) - TA(2) + TT(2) + TU(2) + TCU(2) + TS(2) + TD(1) + TCD(1) + TR(1)$$

The TIC reading at station 2 is:

$$TI(2) = TA(2) - TA(1) + TT(1) + TU(1) + TCU(1) + TS(1) + TD(2) + TCD(2) + TR(2)$$

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

$$\begin{aligned} TI(1) - TI(2) = {} & 2 \cdot TA(1) - 2 \cdot TA(2) + TT(2) - TT(1) + TU(2) - TU(1) + TS(2) - TS(1) \\ & + TD(1) - TD(2) + TR(1) - TR(2) + TCD(1) - TCU(1) - TCD(2) + TCU(2) \end{aligned}$$

The time-scale difference is given by:

TA(1) – TA(2) =	1/2[TI(1)]	(= TIC reading at station 1)
	–1/2[TI(2)]	(= TIC reading at station 2)
	+1/2[TS(1) – TS(2)]	(= Satellite delay difference)
	+1/2[TU(1) – TD(1)]	(= Up/down difference at station 1)
	–1/2[TU(2) – TD(2)]	(= Up/down difference at station 2)
	+1/2[TT(1) – TR(1)]	(= Transmit/receive difference at station 1)
	–1/2[TT(2) – TR(2)]	(= Transmit/receive difference at station 2)
	–1/2[TCD(1) – TCU(1)]	(= Sagnac correction for station 1 including the correction for satellite movement)
	+1/2[TCD(2) – TCU(2)]	(= Sagnac correction for station 2 including the correction for satellite movement).

The last seven terms are the corrections for non-reciprocity. The corrections can be determined and grouped in corrections per station. Each station exchanges the TI(k) data together with the assessment of its own corrections to the other station.

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

2 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. TS(1) = TS(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, e.g. the transatlantic Intelsat satellites. In this case TS(1) and TS(2) or at least the difference TS(1) – TS(2) should be measured before the launch of the satellite or using another accurate time transfer method.

3 Sagnac-effect correction

Due to the movement around the rotation axis of the Earth, both of the earth stations and of the satellite 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 k is given by:

$$\mathrm{TCD(k)} = (\Omega / c^2) \times [\mathrm{Y(k)} \times \mathrm{X(s)} - \mathrm{X(k)} \times \mathrm{Y(s)}]$$

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 (m)

= $r \cos[\mathrm{LA(k)}] \times \cos[\mathrm{LO(k)}]$

X(s): geocentric x-coordinate of satellite (m)

= $R \cos[\mathrm{LA(s)}] \times \cos[\mathrm{LO(s)}]$

Y(k): geocentric y-coordinate of station (m)

= $r \cos[\mathrm{LA(k)}] \times \sin[\mathrm{LO(k)}]$

Y(s): geocentric y-coordinate of satellite (m)

= $R \cos[\mathrm{LA(s)}] \times \sin[\mathrm{LO(s)}]$

r: Earth radius = 6 378 140 m

R: satellite orbit radius = 42 164 000 m

LA: latitude

LO: longitude.

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

Total Sagnac correction TC(12) for clock at station 1 as reference to measure clock at station 2 is:

$$\text{TC}(12) = 1/2\big(\text{TCU}(1) + \text{TCD}(2) - [\text{TCU}(2) + \text{TCD}(1)]\big)$$

Further, 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 directions of the signals: TCU(k) = –TCD(k), so TC(12) = –TCD(1) + TCD(2).

Example for a satellite at 307° E:

LA(VSL) = 52° N, LO(VSL) = 4° E, LO(sat) = 307° E, difference in LO = 57°, TCD(VSL) = +112.42 ns

LA(USNO) = 39° N, LO(USNO) = 283° E, LO(sat) = 307° E, difference in LO = –24°, TCD(USNO) = – 68.83 ns

TC(VSL→USNO): –TCD(VSL) + TCD(USNO) = –181.25 ns

TC(USNO→VSL): –TCD(USNO) + TCD(VSL) = +181.25 ns

VSL: NMi Van Swinden Laboratory, Delft, the Netherlands

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

4 Non-reciprocity effects 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 may be compensated for by a slight adjustment (<17 ms) of emission times. If synchronization errors are not compensated for in this way, the error itself, which may be of the order of 1 ns, requires correction.

5 Ionospheric correction

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

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

where:

TEC: Total Electron Content along the signal path

c: speed of light

f_d and f_u: down and uplink frequencies.

Example: For a high TEC of 1×10^{18} electrons/m^2 and for f_u = 14.5 and f_d = 12.5 GHz this ionospheric delay is equal to 0.859 ns − 0.639 ns = 0.220 ns. So the correction for ½[TU(k) – TD(k)] is typically smaller than –0.11 ns.

6 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 not frequency dependent and so its influence on the up and down propagation delays is equal and no correction is needed.

7 Earth station delay measurement

The difference of the transmit and receive section [TT(k) – TR(k)] including the up and down converters, modulator and demodulator (modem), feeds, wiring, 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 satellite-simulator and calibrated cable.

The last method is the least expensive and can 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 have to be determined as well. This can be done by:

– co-locating the modems and measuring the sum of the transmit delay of one modem and the receive delay of the other;

– by measuring the sum of transmit and receive delay by connecting the IF output signal to the IF input of each of the modems. The transmit delay between the 1 pps transmitted and the appropriate phase reversal in the IF phase modulated output signal of the modem is measured, e.g. by an oscilloscope. The receive delay is found by subtracting the transmit delay from the measured sum of the delays.

8 Data processing

In order to determine the difference between the UTC(k) of the two participating laboratories, one must carefully measure and document the delays which occur in the timing chain of each laboratory. In some laboratories, UTC(k) is a mathematical time-scale. All laboratories have a master clock (clock(k)) which is the physical representation of this time-scale. Each laboratory computes a table of values with the relationship of its master clock to its time-scale [UTC(k) – clock(k)]. Clock(k) can be used as input ref(k) to the modem which generates the PN code which is transmitted. There is a delay [clock(k) – ref(k)] caused by the cabling associated with connecting clock(k) to the modem. The modem generates a 1PPSTX which is related to the transmitted signal which allows the difference [ref(k) − 1PPSTX(k)] with respect to the ref(k) to be measured.

To calculate the difference between the UTC time scales of the two laboratories from [TA(1) – TA(2)] (see § 1), the following applies:

$$
\begin{aligned}
\text{UTC}(1) - \text{UTC}(2) = {} & \text{TA}(1) - \text{TA}(2) \\
& - [\text{UTC}(1) - \text{clock}(1)] \\
& - [\text{clock}(1) - \text{ref}(1)] \\
& - [\text{ref}(1) - \text{1PPSTX}(1)] \\
& + [\text{UTC}(2) - \text{clock}(2)] \\
& + [\text{clock}(2) - \text{ref}(2)] \\
& + [\text{ref}(2) - \text{1PPSTX}(2)]
\end{aligned}
$$

9 Determination of accuracy and stability of the result

The general guidelines of the International Organization for Standardization (ISO) (1993) “Guide to the expression of uncertainty in measurement” should be followed along with the characterization of performance procedures outlined in Recommendation ITU-R TF.538.

10 Performance characteristics of the earth station

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 jitter. The second level concerns the performance characteristics of the earth station as required by the regulatory organizations.

Meeting regulatory requirements do not by themselves guarantee satisfactory two-way operation. Only when the required C/N_0 and carrier level C is delivered to the modem will one get satisfactory results. Operating parameters are determined from a link budget. From the 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 § 2.2 and Annex II of the CCIR Handbook on Satellite Communications (Fixed-Satellite Service), Geneva, 1988.

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, G/T, e.i.r.p., 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.

Electrical performance standards are usually defined by one or more of the following: Recommendations ITU-R S.580 and ITU-R S.465; US FCC regulation 25-209 from the Code of Federal Regulations, Title 47, Parts 20-39; and INTELSAT Earth Station Standard documents for standard C (IESS-203), standard E (IESS-205), standard G (IESS-601), and standard Z (IESS-602) earth stations. Some regions of the world may have other requirements relating to the satellite system, location, classification of user, and other criteria.

ANNEX 2

Information on the data format for data exchange

1 Introduction

The data file begins with a header which should contain all data that are not considered to change during the measurement session. The subsequent data lines contain all data that are expected to change during the session. Some data lines contain information for experimental purposes (e.g. the once-per-second readings) whereas other data lines contain information directly for operational use (e.g. the quadratic “best fit” for a session).

2 Required information

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

The identification of the participating stations by an ASCII character should be done, and PN codes and a clean carrier offset frequency should be assigned.

As an example, see Table 1.

TABLE 1

Laboratory designation (ASCII character)	TX code (MITREX)	Clean carrier offset (kHz from centre frequency)
A	0	−20
B	1	0
C	2	+20
D	3	−40
E	4	+40
F	5	+60
G	6	+80
H	7	−80

2.2 Session parameters

A plan for a session should contain the following information:

– satellite identification: name, longitude, orbital parameters, transponder channel, satellite equipment non-reciprocity;
– station designations;
– TX-codes and RX-codes;
– link budget;
– earth station TX and RX frequencies;
– operator's name;
– start date and time;
– preparation time for each session (equal to the pause between successive sessions);
– duration of each session;
– the way to exchange the generated data files.

2.3 Local earth station(k) parameters

Each station should keep on file the following information:

– antenna coordinates (x, y, z in the IERS terrestrial reference frame);
– earth station designator;
– transmit power e.i.r.p. (W);
– G/T of the receiver;
– modem: manufacturer, model, type, serial number;
– time interval counter: manufacturer, type, serial number;
– antenna: manufacturer, type, diameter, gain;
– delay calibration: date, method, results;
– optional: record during the sessions the measured TX-RX delay, the C/N_0, the environmental parameters at the antenna (temperature, humidity, barometric pressure, weather conditions).

Any change in station parameters and equipment should be reported.

3 Data format

3.1 General

The conventions and symbols reported below apply completely to the data format described in § 3.2 and partly to that in § 3.3.

LAB:	laboratory identification (e.g., according to the Bureau international des poids et mesures (BIPM) convention)
jjjjj:	modified Julian date
hh:	UTC hour
mm:	UTC minute
ss:	UTC second
L:	designation of Local laboratory by an ASCII character
R:	designation of Remote laboratory by an ASCII character
*:	indication of the start of a line of text
S:	indication of the sign of the subsequent value
[ ]:	designation of an option
|:	designation of a choice
0.nnnnnnnnnnnn:	value of a time interval (s) (12 decimals = 1 ps resolution).

DATA FILE NAME:

Ljjjjjhh.mmR
where jjjjj, hh, mm give the NOMINAL UTC start date of the TWSTFT session.

HEADER:

* Ljjjjjhh.mmR
* UTC (LAB) – CLOCK = S0.nnnnnnnnnnnn [jjjjj hhmmss]
* CLOCK – 1PPSREF = S0.nnnnnnnnnnnn [jjjjj hhmmss]
* 1PPSREF – 1PPSTX = S0.nnnnnnnnnnnn [jjjjj hhmmss]
* Any other parameter of the form: PARAMETER = Value [units] [jjjjj hhmmss]
* DATA = [1PPSTX – 1PPSRX] | [1PPSREF – 1PPSRX] | [..]

where jjjjj, hhmmss optionally give the UTC data at which the indicated value is taken.

3.2 Report of the individual 1 s measurements

DATA FILE FORMAT:
the HEADER immediately followed by the DATA.

DATA:

```
jjjjj  hhmmss  0.nnnnnnnnnnnn
jjjjj  hhmmss  0.nnnnnnnnnnnn
  ⋮       ⋮          ⋮
jjjjj  hhmmss  0.nnnnnnnnnnnn
```

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

EXAMPLE:

File A4926610.56B (data measured at station A from a TWSTFT session with station B on MJD 49266, scheduled at 1056 h UTC):

```
*      A4926610.56B
*      UTC (LAB A) – CLOCK  = –0.000000123456 49266 101000
*      CLOCK – 1PPSREF      =   0.000000012345
*      1PPSREF – 1PPSTX     = +0.000000001234 49266 102059
*      DATA = 1PPSTX – 1PPSRX
49266  105616 0.270924666406
49266  105617 0.270924663805
49266  105618 0.270924660170
49266  105619 0.270924657628
49266  105620 0.270924654270
49266  105621 0.270924651106
```

3.3 File format reporting results of a quadratic fit

3.3.1 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 tracks 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 cursive letters have to be replaced by actual strings or values, respectively. 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 (including a possible sign).

3.3.2 File name

The file name consists of **TW** (for two-way satellite time and frequency transfer), the designation of the laboratory (*LLLL*, up to four characters according to the acronyms of the laboratories as given in the Annual Report of the BIPM Time Section) and the Modified Julian Date as given in the first data line (the last three digits as file extension): **TW***LLLLMM.MMM* (for example TWTUG50.091).

3.3.3 Header

Number of columns in header lines are limited to 78.

```
.........1.........2.........3.........4.........5.........6.........7........
123456789012345678901234567890123456789012345678901234567890123456789012345678

* 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: SSSSSSSSSSSSSSSSS  NLO: D ddd mm ss.sss  XPNDR: +nnnn.nnn ns

*           SAT-NTX: fffff.ffff MHz  SAT-NRX: fffff.ffff MHz

* CAL   CCC TYPE: TTTTTTTTTTTTTTTTT  MJD: MMMMM  EST. UNCERT.: nnnn.nnn ns
* LOC-MON   [YES] [NO]
* MODEM     TYPE, SERIAL NUMBER
* COMMENTS  SSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSS

*
```

TWLLLLMM.MMM	File name (see § 3.3.2)
FORMAT	Format version (from 01 to 99).
LAB	Acronym of the laboratory where the observations are performed. For the acronyms of the laboratories see the Annual Report of the BIPM Time Section.
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 § 3.3.4), which points to a specific LINK line of the file header.

SAT Satellite identification according to designation of satellite operating agency or international space community.

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 satellite (MHz). This frequency corresponds to the receive frequency of the local earth station.

SAT-NRX Nominal receive frequency of satellite (MHz). This frequency corresponds to the transmit frequency of the local earth station.

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 Date and the estimated uncertainty of the calibration:

CCC Calibration identification contained in each data line (data line header: CI, see § 3.3.4), 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 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, for example:

GPS Global Positioning System.

PORT CLOCK Portable clock.

Different types may be used for the same link resulting in different data lines.

MJD Modified Julian Date of the calibration.

EST.UNCERT. Estimated 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.

As many lines and columns as necessary can be used.

COMMENTS Comment lines as many as necessary.

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

3.3.4 Data line

For the format of a data line see Appendix 1 to 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.

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 CCDS Working Group on Two-Way Satellite Time Transfer (for examples see § 3.3.6)

MJD STTIME Nominal start date (MJD and time (h, min, s)) referenced to UTC.

NTL Nominal track length (s) (nominal date of last sample minus nominal date 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.

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) (date of last sample minus date of first sample of the quadratic fit).

REFDELAY Delay of the reference with respect to UTC(LAB) (s). The calculation of this term depends on the measurement set-up at each laboratory. For the usually employed measurement set-up (PPSTX starts two-way measurements) the reference delay is the sum (UTC(LAB)-CLOCK) + (CLOCK-REF) + (REF-PPSTX).

RSIG Standard deviation of the mean of REFDELAY (ns).

CI Calibration identification is a pointer to the file header, which informs about the calibration type, the Modified Julian Date and the estimated uncertainty of the calibration.

The assignment of a calibration identification has to be coordinated on an international basis (such as by the CCDS Working Group on Two-Way Satellite Time Transfer) for the laboratories involved in a specific calibration campaign. Using an independent time transfer system (e.g. GPS) calibrations are only possible between pairs of laboratories, therefore calibration identifications have to be assigned for pairs of laboratories (for examples see § 3.3.6).

S Calibration switch (either "0"or "1"). It indicates which terms of the two-way equation are included in the calibration result CALR and which equation must therefore be used for the computation of the clock differences (see § 3.3.5).

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).

S = 1 The calibration result CALR includes all terms of the two-way equation except the time transfer measurements TW and the reference measurements REFDELAY of the local and remote station, respectively. This is the case using an independent time transfer system, e.g. GPS.

CALR Calibration result (ns).

ESDVAR Monitored differential earth station delay variations (ns) (referred to the differential earth station delay observed at calibration time if a calibration is available). All earth station and modem delay changes have to be included.

ESIG	Standard deviation of the mean of ESDVAR (ns).
TMP	Outside temperature (°C).
HUM	Outside relative humidity (%).
PRES	Air pressure (mbar).

3.3.5 Computation of clock differences

S = 0: $UTC(LAB_1) - UTC(LAB_2)$ =	$+0.5(TW_1 + ESDVAR_1) + REFDELAY_1$	Data line lab 1
	$-0.5(TW_2 + ESDVAR_2) + REFDELAY_2$	Data line lab 2
	+0.5 EARTH ROT.CORR.	Header lines lab 1 and lab 2
	+0.5 IONOSPHERIC CORR.	Header lines lab 1 and lab 2
	$+0.5\ CALR_1$	Data line lab 1
	$-0.5\ CALR_2$	Data line lab 2
	+0.5 XPNDR	Header line lab 1
S = 1: $UTC(LAB_1) - UTC(LAB_2)$ =	$+0.5(TW_1 + ESDVAR_1) + REFDELAY_1$	Data line lab 1
	$-0.5(TW_2 + ESDVAR_2) - REFDELAY_2$	Data line lab 2
	+CALR	Data line lab 1

The knowledge of the positions of the earth stations and the satellite allows to calculate the EARTH ROT.CORR. (Sagnac effect) and the knowledge of the transmit and receive frequencies allow to calculate the IONOSPHERIC CORR.

3.3.6 Examples

(See Appendix 2 to Annex 2.)

APPENDIX 1
TO ANNEX 2

1 DATA LINE

```
         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 degC  %  mbar
LLLLnn LLLLnn LL MMMMM hhmmss nnn +0,nnnnnnnnnnnn n,nnn nnn nnn +0,nnnnnnnnnnnn n,nnn CCC i +nnnn,nnn +nnnn,nnn n,nnn +nn nnn nnnn
```

APPENDIX 2
TO ANNEX 2

EXAMPLES

The examples contain actual and fictious data (especially for calibration).

1 DATA FILES

```
* TWUSNO49.933
* FORMAT    01
* LAB       USNO
* REV DATE  1995-07-10
* ES USNO01 LA: N  38 55 00.000      LO: W  77 04 00.000   HT:    51.30 m
* REF-FRAME WGS84
* LINK   04 SAT: IS706               NLO: W  53 00 00.000  XPNDR: 99999.999 ns
*           SAT-NTX: 11922.3750 MHz  SAT-NRX: 14221.6275 MHz
* CAL   002 TYPE: GPS                MJD: 49639  EST. UNCERT.:    5.000 ns
* CAL   003 TYPE: GPS                MJD: 49649  EST. UNCERT.:    5.000 ns
* LOC-MON   NO
* MODEM     MITREX 2500A
*
* 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
USNO01  TUG01 04 49933 140200 299  0.263265762933 1.529 300 299  0.000001334100 9.999 002 1   296.350 99999.999 9.999  32  63  994
USNO01  NPL01 04 49933 141000 299  0.260419315503 0.613 300 299  0.000001334200 9.999 999 0 99999.999 99999.999 9.999  32  63  994
USNO01  VSL01 04 49933 141800 299  0.261451406897 0.387 300 299  0.000001334200 9.999 999 0 99999.999 99999.999 9.999  32  63  994
USNO01  PTB01 04 49933 143400 299  0.262748501558 1.822 233 232  0.000001334240 9.999 003 1   449.500 99999.999 9.999  32  63  994
```

```
* TWTUG49.933
* FORMAT    01
* LAB       TUG
* REV DATE  1995-07-10
* ES  TUG01 LA: N  47 04 01.578      LO: E  15 29 36.570   HT:   538.14 m
* REF-FRAME ITRF88
* LINK   03 SAT: IS706               NLO: W  53 00 00.000  XPNDR:     0.000 ns
*           SAT-NTX: 12549.7475 MHz  SAT-NRX: 14044.7475 MHz
* LINK   04 SAT: IS706               NLO: W  53 00 00.000  XPNDR: 99999.999 ns
*           SAT-NTX: 12726.6275 MHz  SAT-NRX: 14217.3750 MHz
* CAL   001 TYPE: PORT ES REL        MJD: 49640  EST. UNCERT.:    5.000 ns
* CAL   002 TYPE: GPS                MJD: 49639  EST. UNCERT.:    5.000 ns
* LOC-MON   YES
* MODEM     MITREX 2500, SN1194
* COMMENTS Since 1995-07-10 a new satellite (same position as the old one) is used.
*
* 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
 TUG01  TUG01 03 49933 100000 299  0.273757169304 0.612 300 299  0.000000237687 0.003 001 0  -720.000     0.689 0.123  26  42  957
 TUG01  NPL01 03 49933 100600 299  0.270911455763 0.328 300 299  0.000000237687 0.003 001 0  -720.000     0.689 0.123  26  42  957
 TUG01  PTB01 03 49933 101200 299  0.273242494495 0.458 300 299  0.000000237687 0.003 001 0  -720.000     0.689 0.123  26  42  957
 TUG01  FTZ01 03 49933 101800 299  0.272511114690 0.416 300 299  0.000000237687 0.003 001 0  -720.000     0.689 0.123  26  42  957
 TUG01  OCA01 03 49933 103000 299  0.271282560840 0.969 300 299  0.000000237687 0.003 001 0  -720.000     0.689 0.123  26  42  957
 TUG01 USNO01 04 49933 140200 299  0.263269499027 0.475 300 299  0.000000237694 0.003 002 1  -296.350    -3.280 0.236  27  38  955
 TUG01 NIST01 04 49933 141000 299  0.268868858338 0.405 300 299  0.000000237693 0.003 999 0 99999.999    -3.280 0.236  27  38  955


* TWPTB49.933
* FORMAT    01
* LAB       PTB
* REV DATE  1995-07-10
* ES  PTB01 LA: N  52 17 49.787      LO: E  10 27 37.966   HT:   143.406m
* REF-FRAME WGS84
* LINK   03 SAT: IS706               NLO: W  53 00 00.000  XPNDR:     0.000 ns
*           SAT-NTX: 12549.7475 MHz  SAT-NRX: 14044.7475 MHz
* LINK   04 SAT: IS706               NLO: W  53 00 00.000  XPNDR: 99999.999 ns
*           SAT-NTX: 12726.6275 MHz  SAT-NRX: 14217.3750 MHz
* CAL   001 TYPE: PORT ES REL        MJD: 49632  EST. UNCERT.:    3.000 ns
* CAL   003 TYPE: GPS                MJD: 49649  EST. UNCERT.:    5.000 ns
* LOC-MON   NO
* MODEM     MITREX 2500A

* 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
 PTB01  PTB01 03 49933 100000 299  0.272722644071 0.614 300 299  0.000000802678 9.999 001 0 -1052.000 99999.999 9.999 999 999 9999
 PTB01  OCA01 03 49933 100600 299  0.270763375457 1.175 300 299  0.000000802678 9.999 001 0 -1052.000 99999.999 9.999 999 999 9999
 PTB01  TUG01 03 49933 101200 299  0.273236013639 0.954 300 299  0.000000802678 9.999 001 0 -1052.000 99999.999.9.999 999 999 9999
 PTB01  NPL01 03 49933 101800 299  0.270390245192 0.379 300 299  0.000000802678 9.999 001 0 -1052.000 99999.999 9.999 999 999 9999
 PTB01 USNO01 04 49933 143400 299  0.262745748275 0.621 300 299  0.000000805499 9.999 003 1  -449.500 99999.999 9.999 999 999 9999
 PTB01 NIST01 04 49933 144200 299  0.268345111620 0.515 300 299  0.000000805499 9.999 999 0 99999.999 99999.999 9.999 999 999 9999
```

2 COMPUTATION OF CLOCK DIFFERENCES

```
UTC(TUG)-UTC(PTB):  MJD 49933, 10:12:00 UTC, CI 001, LI 03
UTC(TUG)-UTC(PTB)=  + 0.5(0.273242494495 + 0.689E-9) + 0.000000237687
                           - 0.5(0.273236013639 + 0       ) - 0.000000802678
                           + 0.5(-37.4E-9)
                           + 0
                           + 0.5( -720.000E-9)
                           - 0.5(-1052.000E-9)
                           + 0.5(0.000E-9)
UTC(TUG)-UTC(PTB)=  +2823.1 ns on MJD 49933 at 10:14:30 UTC

UTC(PTB)-UTC(USNO): MJD 49933, 14:34:00 UTC, CI 003, LI 04
UTC(PTB)-UTC(USNO)= + 0.5(.262745748275 + 0) + 0.000000805499
                           - 0.5(.262748501558 + 0) - 0.000001334240
                           + (-449.500E-9)
UTC(PTB)-UTC(USNO)= -2354.9 ns on MJD 49933 at 14:36:30 UTC

UTC(USNO)-UTC(TUG)= -473.7 ns on MJD 49933 at 14:04:30 UTC
```

3 IDENTIFICATION AND DESCRIPTION OF SATELLITE LINKS

LI	LINK	SAT	NLO			XPNDR DELAY (ns)	SAT-NTX (MHz)	SAT-NRX (MHz)	Remarks
			dd	mm	ss				
01	EU-EU	IS513	53	00	00 W	0.000	12543.4025	14038.4025	
02	EU-USA	IS513	53	00	00 W	448.000	12644.8275	14139.8275	For European earth stations
		IS513	53	00	00 W	–448.000	11844.8275	14139.8275	For United States earth stations
03	EU-EU	IS706	53	00	00 W	0.000	12549.7475	14044.7475	
04	EU-USA	IS706	53	00	00 W	9999.999	12726.6275	14217.3750	For European earth stations
		IS706	53	00	00 W	9999.999	11922.3750	14221.6275	For United States earth stations

4 IDENTIFICATION AND DESCRIPTION OF CALIBRATIONS PERFORMED

CI	TYPE	MJD	CALR (ns)	EST. UNCERT. (ns)	Remarks
001	PORT ES REL				Visit of portable earth station (USNOxx) during October 1994 to OCA, LPTF, NPL, VSL, PTB, FTZ, TUG, USNO, NIST
		49632	–1052.000	3.000	PTB01
		49640	–720.000	5.000	TUG01
002	GPS	49639	–296.350	5.000	Calibration of link TUG01-IS706-USNO01 using the independent time transfer system GPS (computed from reported GPS data)
003	GPS	49649	–449.500	5.000	Calibration of link PTB01-IS706-USNO01 using the independent time transfer system GPS (computed from reported GPS data)