PRECISE TIME TRANSFER TO THE NASA SPACEFLIGHT TRACKING AND DATA NETWORK (STDN) VIA THE TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)

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ABSTRACT

Data communication via the Tracking and Data Relay Satellite (TDRS) is to become available to users in 1980. The ranging and data services provided by the Tracking and Data Relay Satellite System (TDRSS) are to be an integral part of NASA's post-1980 Spaceflight Tracking and Data Network (STDN). The synchronous orbit TDR satellites are to be positioned so as to provide near worldwide coverage, depending upon user satellite orbit or user earth location. An essential service that NASA will provide to its own tracking network (STDN) is precise time transfer using the TDR satellites. The network ground station's transmit/receive hardware will be essentially a non-flight version of the TDRSS user transponder.

The paper discusses the time transfer technique and the ground Time Transfer Unit (TTU) which contains a microprocessor for determining and averaging various time interval measurements. The TTU interfaces with the local ground station timing system and with the transponder that will be available at the NASA Network sites for TDRSS orbit determination.

Time transfer communication between the TDRSS ground station at White Sands and the STDN stations will be in a Multiple Access service standard mode of operation. This mode uses a combination of pseudorandom (PRN) codes and data modulation for ranging and telemetry. A selected code state indicator (e.g., the "all 1's" state) provides stable event markers.

To transfer time via the TDRSS, the time interval between a specific event marker and the master station clock's 1 PPS is measured. A similar interval is measured by the user as his transponder receives the PRN code and hence the event markers. The time interval measurements and other information are exchanged between master and user by forward and return telemetry. The master makes a second time interval measurement to allow estimation of the forward delay time.

The Time Transfer Unit includes a microprocessor and associated peripheral chips used for synchronizing and multiplexing the time transfer telemetry frame and for computing clock error. The time interval measurements required will be obtained from precision time interval counters. The error in the clock difference measurement is expected to be less than 40 nanoseconds and to be available once each second. The total elapsed time required to complete a time transfer should be less than five minutes.

1.0 SUMMARY OF THE TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)

1.1 General

The tracking and Data Relay Satellite System (TDRSS) is being developed for NASA by an industry team composed of Western Union Space Communications Inc. (WU), Harris Electronic Systems Division (HESD), and TRW Systems Group. The ranging and data services provided by TDRSS are to become an integral part of NASA's post-1980 Spaceflight Tracking and Data Network (STDN).

1.2 Coverage

Data communication accessibility will be nearly worldwide depending upon user satellite altitude and inclination. This coverage is to be provided by three synchronous orbit relay satellites, two of which (TDRS East and TDRS West) are spaced 130 apart in longitude. Considering remote ground stations as potential TDRSS users to receive precise time transfer, the zone of coverage would include East Longitude locations to the east coast of Africa and West Longitude locations to the west coast of Australia. This region of coverage at the earth's surface includes all currently anticipated STDN stations. A basic illustration of communication relay via TDRSS is shown in Figure 1.1.

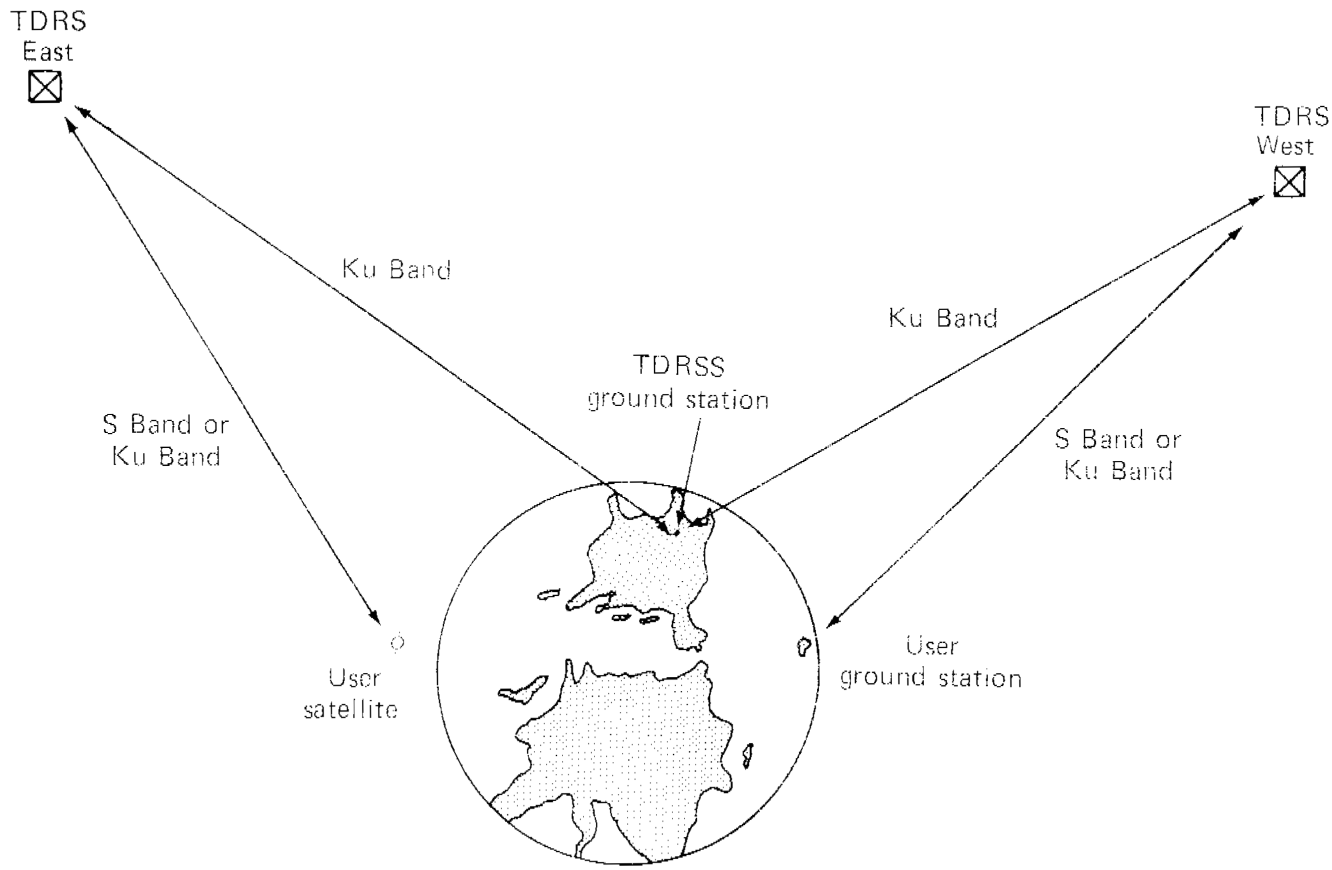


Fig. 1.1 Communication Relay via the Tracking Data Relay Satellite System

Tracking and data relay satellite (TDRS)

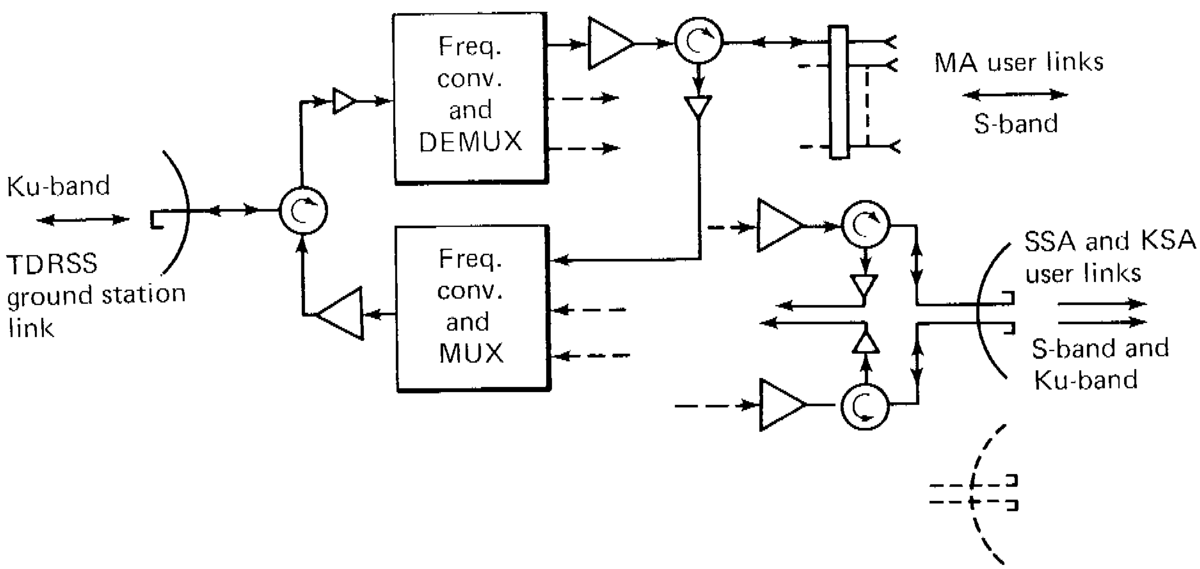


Fig. 1.2 Forward and Return Relay via the Tracking and Data Relay Satellite (TDRS)

1.3 TDRSS Services

Two basic types of service will be provided by TDRSS, Single Access and Multiple Access. For Single Access service, each TDR satellite has two steerable dual-feed antennas. The dual feeds provide for S-Band and Ku-Band communication (SSA and KSA) to and from users. For Multiple Access (MA) service, each TDR satellite has a planer S-Band array antenna capable of both forward and return beam forming. Forward link beam forming to a user is done at the TDR satellite and return link beam forming from a user is done at the TDRSS ground station. Each MA user, therefore, has the equivalent of a directed beam.

Forward and return relay between the TDRSS ground station and the TDR satellites is at Ku-Band. The required multiplexing, demultiplexing and frequency translations to and from the user are done at the TDR satellite. Figure 1.2 is a simplified block diagram of the signal flow through a TDR satellite.

1.4 TDRSS Signal Design

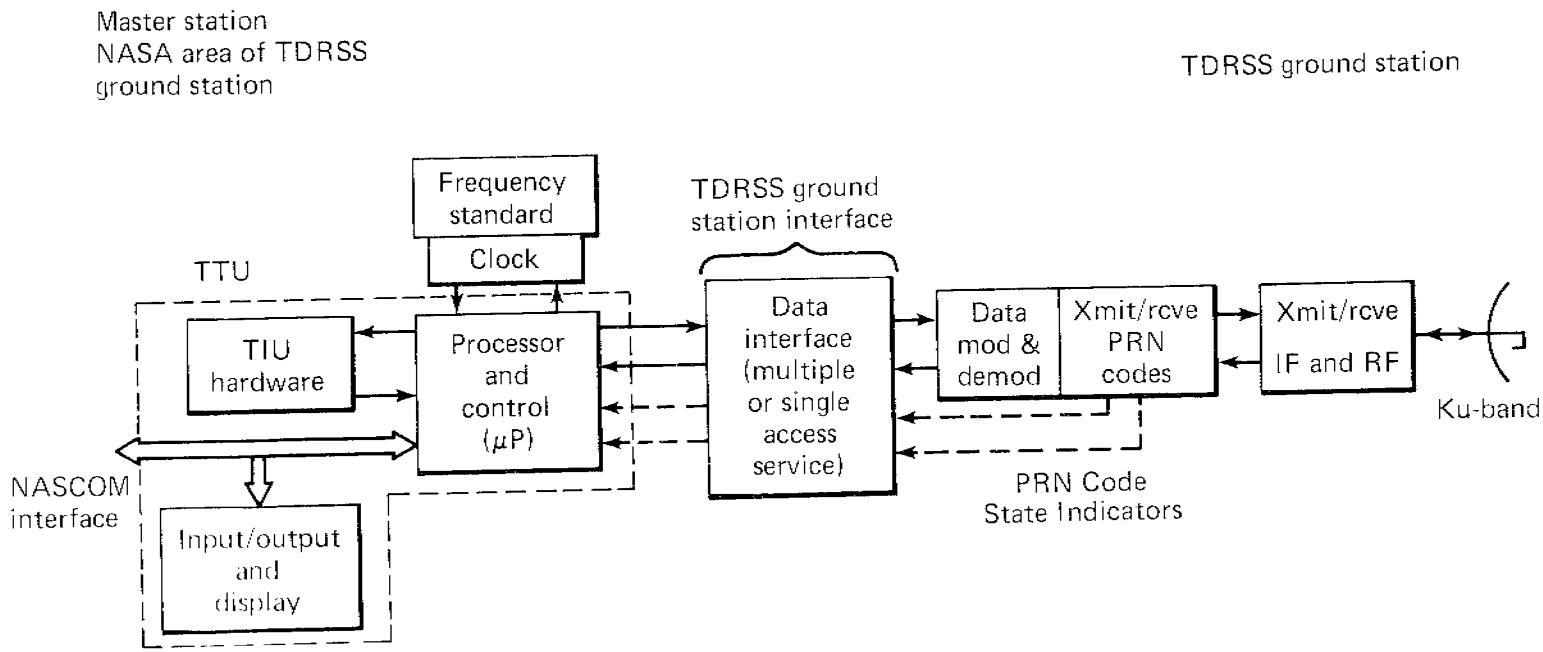
In order to best satisfy the combined requirements of limited radiation flux density, Single and Multiple Access ranging and data services, and individual beam forming for each Multiple Access user, a pseudorandom (PRN) code signal design was chosen for TDRSS.

The capability of simultaneous ranging and data communication is directly applicable to time transfer. Ranging is accomplished by synchronized forward and return link PRN codes in a "round trip" or "two way" ranging mode (TDRSS Mode 1). Forward and return telemetry data are modulated onto the respective codes allowing simultaneous two-way data transfer. The PRN code "epoch" signals or "state indicators" serve as event markers for time transfer. Signal margins are such that these markers will be quite stable and code acquisition times relatively short.

1.5 TDRSS Interface

The basic type of interface between users and TDRSS is a data interface, available with both Single and Multiple Access services. Baseband digital data and data clock are applied at the TDRSS ground station to a forward link data interface. Baseband digital data and data clock are returned from the user via a return link data interface. The forward and return PRN code "epochs" or "state indicators" will be utilized for time transfer to the NASA ground network stations (STDN).

A block diagram of the time transfer hardware and the interface with the TDRSS ground station at White Sands is shown in Figure 1.3.



TIU = Time interval counter units
μP = Microprocessor

Fig. 1.3 Time Transfer Hardware and TDRSS Ground Station Interface

The basic time transfer unit (TTU) includes the microprocessor with associated peripheral hardware, the time interval counting units, and the frequency standard and clock.

A block diagram of the STDN station TTU and TDRSS interface hardware is shown in Figure 1.4. Essentially the same hardware is used here as issued at the TDRSS ground station except that the transmit/receive interface is with a TDRSS user transponder.

2.0 TDRSS TIME TRANSFER TECHNIQUE

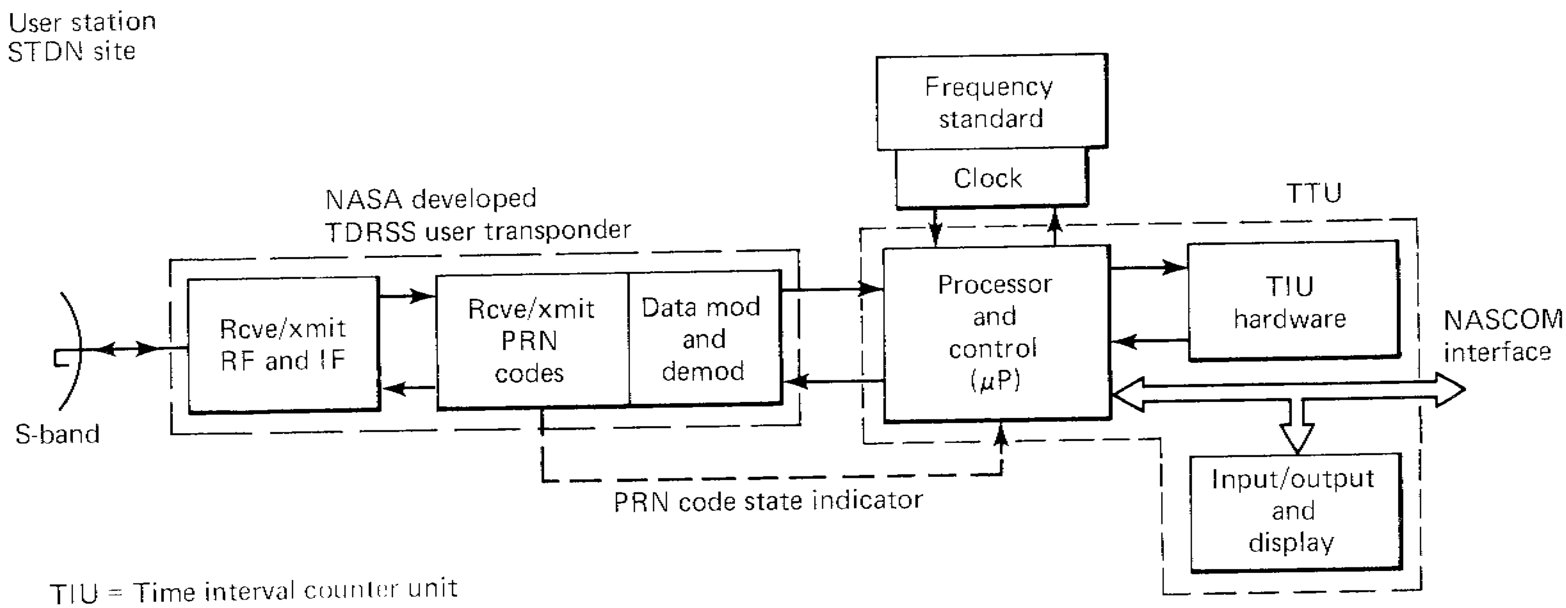
For the purposes of this paper, the transfer of time is defined to mean the determination of the difference between the clock times of two physically separated stations. It is assumed that each station has a clock 1 PPS signal derived from and having the accuracy of its own time standard. This allows the time interval between clocks to be measured as the time interval between occurrences of the stations' respective 1 PPS signals. The objective of the technique described herein is to determine the time interval between those 1 PPS signals (i.e., the clock error, ϵ).

2.1 Clock Error Calculation

The technique described below can assume a Master/Slave relationship between the stations where in fact the master station would be the NASA terminal at the White Sands TDRSS ground station. The slave station would be one of the STDN tracking stations or other suitably equipped TDRSS user. The implementation could be such that essentially the same hardware but slightly different software (Section 3.0 discusses implementation) would make the two stations reciprocal, so that either station could act as the master. This would be advantageous if a given station was required to have the capabilities of either master or slave, as in a chain-type time transfer.

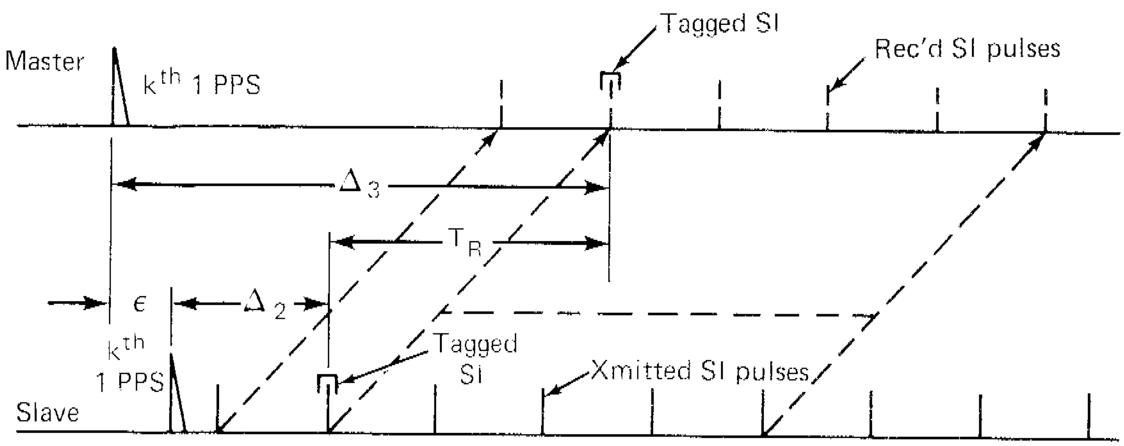
To determine the clock error, ϵ, the master must know when the slave's 1 PPS occurred relative to his own. This is achieved by having both master and user measure the time interval from their respective 1 PPS signals to a common reference. The common reference is an epoch or state indicator signal of the PRN code being relayed between master and slave, via the TDR satellite.

As this code is generated, the code vectors or state indicators (SI's) occur repeatedly, once for each full cycle of the code. To avoid ambiguity, one specific SI is selected or tagged so that both slave and master refer their measurement to the same SI. A timing diagram illustrating the intervals to be measured (Δ_2 and Δ_3) is given in Figure 2.1a. From the diagram, one can express the clock error as;

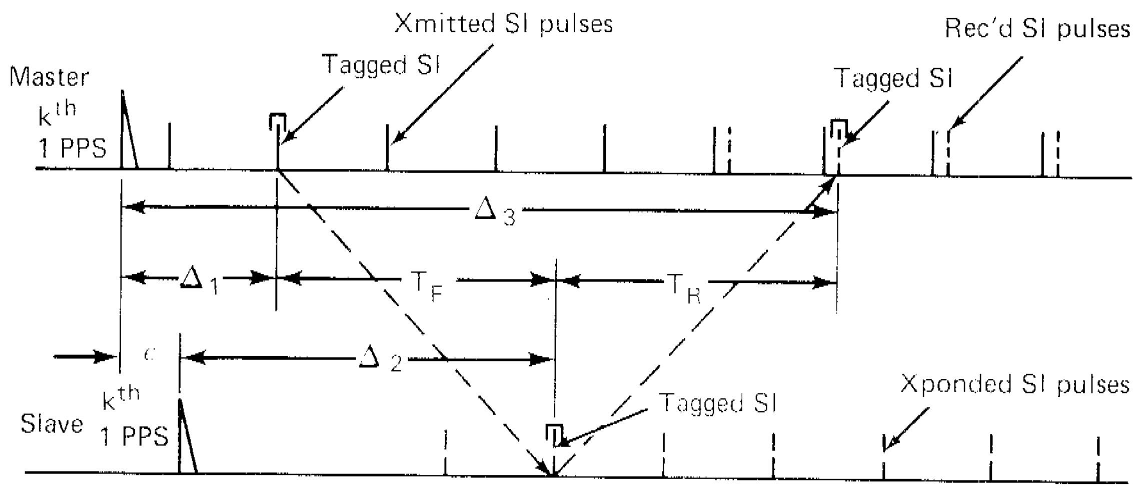


TIU = Time interval counter unit
μP = Microprocessor

Fig. 1.4 Time Transfer Hardware and STDN User Interface



(a) One-way (Slave-to-master) Time
Transfer SI Timing Diagram



(b) Two-way Time Transfer SI
Timing Diagram

Fig. 2.1 Basic Time Transfer Signals and Time Intervals

$$\epsilon = \Delta_3 - \Delta_2 - T_R \qquad (2.1\text{-}1)$$

This represents a "one way" or "return only" method of time transfer in which Δ and Δ are the intervals measured by the slave and master, respectively, and T_R is the return link path delay from slave to master. (It is assumed that any hardware delays have been taken into account; this will be discussed in Section 4).

To actually calculate ϵ, the delay T_R must be determined. For a one-way link of user-to-master (TDRSS Mode 2 return link only), T_R would have to be calculated using ephemeris data on the TDR satellite, as well as the exact locations of slave and master.

A second method of determining T_R is to estimate it from measurements using a two-way link (TDRSS Mode 1). In this mode, the master originates the PRN code; the slave receives and retransmits the code, and makes his Δ_2 measurement which is also sent back during the next one-second measurement interval. The returning code enables the master to make not only an initial interval measurement (Δ_1), but also a second interval measurement (Δ_3). The measurements are made from his 1 PPS to the tagged S1 as it is being transmitted (Δ_1) and received (Δ_3). Figure 2.1b illustrates the timing for this situation.

From Figure 2.1b one can see that the total path delay, T_F+T_R is;

$$T_F+T_R = \Delta_3 - \Delta_1 \ .$$

where T_F is the forward link path delay from master to slave. Hence, the two measurements made by the master, Δ_1 and Δ_3, allow estimation of the path delay. If we now assume that the forward and return delays through the satellite hardware are equal and that the satellite is motionless relative to the earth, the return path delay, T_R, is equal to the forward path delay, T_F. Using this assumption and Eq. (2.1-2), Eq. (2.1-1) becomes;

$$\epsilon = \frac{\Delta_3-\Delta_1}{2} - (\Delta_2-\Delta_1) \ . \qquad (2.1\text{-}3)$$

2.3 Summary

Several assumptions were made to obtain the simple result of Eq. (2.1-3), namely equal forward and return delays through satellite, master and user station hardware, and a "stationary" satellite. The influence of hardware delay and satellite motion in the clock error estimate are illustrated in Section 4.

Satellite motion can cause an error in the computed value of of about 25 nanoseconds over an interval of about 1 minute for a linear radial motion of 30 meters/sec. The time transfer system proposed herein is capable of estimating the first order (linear) motion of the satellite using the time interval measurements. With a set of measurements being made once each second (corresponding to each 1 PPS), the previous two seconds of measurements will be sufficient to estimate linear motion. Section 4 contains a more complete description of satellite motion, hardware delay, and signal jitter contributions to time transfer error.

3.0 IMPLEMENTATION OF THE TDRSS TIME TRANSFER TECHNIQUES

Section 2 discussed the general technique used to effect a "time transfer" using the TDRSS. The details of implementation were ignored. These will now be discussed.

3.1 Data Link

A number of questions were left unanswered in Section 2, such as how the master obtains the measurements made at the slave station, and especially how one particular SI is "tagged" so that both stations recognize it. (This essential feature will be described in Section 3.2.2, paragraph 2.) Communication through the TDRSS data link and the format of this communication provide the answers. Modulated onto the PRN code is data in block form as shown in Table 3.1. This data, generated by the Time Transfer Terminal (TTU), is used to transfer such required information as:

a. The quantities necessary for clock error calculations including time interval measurements, time-of-day, and, in a "one-way" situation, range information perhaps in the form of position constants.

b. A status word used to communicate between master and user such things as data validity, loss of frame, end of transmission, and others.

c. Sync words which indicate the beginning of the telemetry frame and also generate a "range gate" to resolve the state indicator (SI) ambiguity by tagging a particular SI. This is discussed in more detail in a later subsection.

d. A sixteen-bit SUMCHK is used to provide transmission error detection since no allowance was made for word parity. The SUMCHK holds the complement of the modulo 2^{16} sum of the contents of the previous 27 bytes. In addition, the sync words, frame ID, and status word also help maintain frame integrity.

Sufficient information is included in the formats to allow either master or user to calculate the error between clocks.

Table 3.1

TDRSS Time Transfer
Telemetry Frame Format — k^{th} Interval

Byte No.	Master TLM Description	User TLM Description
1	Frame Sync	Frame Sync
2	Frame Sync	Frame Sync
3	Frame ID	Frame ID
4	STATUS WD	STATUS WD
5	STATION ID	STATION ID
6	TIME-OF-DAY, DAYS	TIME-OF-DAY, DAYS
7	TIME-OF-DAY, DAYS	TIME-OF-DAY, DAYS
8	TIME-OF-DAY, HRS	TIME-OF-DAY, HRS
9	TIME-OF-DAY, MINS	TIME-OF-DAY, MINS
10	TIME-OF-DAY, SECS	TIME-OF-DAY, SECS
11	Δ_1 (k-1)	Δ_2 (k-1)
12	Δ_1 (k-1)	Δ_2 (k 1)
13	Δ_1 (k-1)	Δ_2 (k-1)
14	Δ_1 (k 1)	Δ_2 (k-1)
15	Δ_1 (k-1)	Δ_2 (k-1)
16	Δ_3 (k-1)	ϵ (k-2)
17	Δ_3 (k-1)	ϵ (k-2)
18	Δ_3 (k-1)	ϵ (k-2)
19	Δ_3 (k-1)	ϵ (k-2)
20	Δ_3 (k-1)	ϵ (k-2)
21	Position Const. ID	SPARE
22	Position Const.	SPARE
23	Position Const.	SPARE
24	Position Const.	SPARE
25	Position Const.	SPARE
26	SPARE	SPARE
27	SPARE	SPARE
28	SUMCHK (LSB)	SUMCHK (LSB)
29	SUMCHK (MSB)	SUMCHK (MSB)
30	ETX (End of Text)	ETX (End of Text)

The data frames include thirty eight-bit bytes (or words) for a total of 240 bits. At the proposed bit rate of 1200 BPS (a standard modem baud rate), the frame period is 200 msecs. The resulting byte period is 6.7 msecs, and the bit period is 0.83 msecs. It is suggested that all numeric data be in a packed BCD format (two decimal digits per byte). This allows the use of the data-independent values 10_{10}-15_{10} in 4-bit nibbles for conveying alphabetic information such as sync words, end-of-text (ETX), and frame and user ID.

3.2

The hardware used to generate, format, and control the transmission and reception of the data frame is shown in Fig. 3.1 for both master and slave. This hardware must also accept the necessary inputs and make all calculations required to determine clock error, as well as provide an interface to the ground network via NASCOM. For discussion purposes, this hardware is separated into three general areas:

1. TDRSS (ground station and user transponder) equipment.

2. Equipment which provides various required inputs to the processor.

3. The processor unit.

3.2.1

The TDRSS equipment is used to provide the communications link between master and slave. It also provides a common event marker reference (the PRN code SI pulses) and a means of relaying the data involved.

3.2.2

The second level hardware includes the items indicated below.

1. Time interval counters are required to measure the Δ_i's.

2. Logic gates and latches are required to provide timing synchronization for the interval counters via START/STOP pulses and synchronization of certain interrupts. These units also tag or gate the proper SI pulse using a Frame Sync detection signal. The tagged SI is in turn latched as a low level into the interval counter, thus stopping the Δ_1 count which had been started by the 1 PPS via the same latch. Hence, Δ_1 is a measure of the interval between the 1 PPS and the first SI pulse following the Frame Sync words. Since the data frame is now referenced to the PRN code (transmission is initiated by another SI pulse),

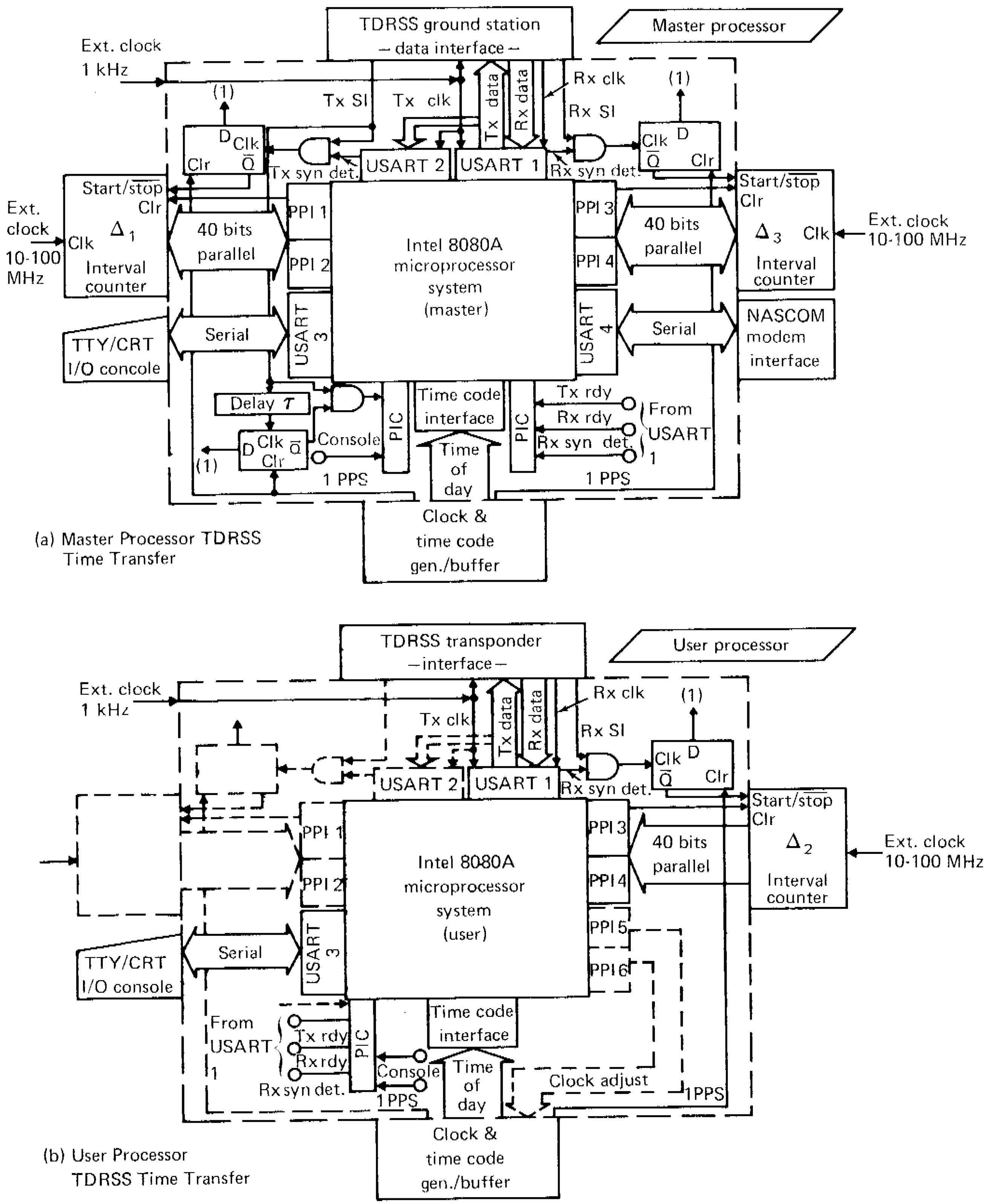


Fig. 3.1 Time Transfer Processor

the tagged SI pulse will always be the first one following the Frame Sync. (During reception of a "turned-around" code, the same sequence occurs, yielding the interval Δ_3.)

3. The frequency standard, station clock, and time code generator/buffer hardware provide the 1 PPS signals and allow all data frames to be time tagged (hours/minutes/seconds).

4. A NASCOM interface is required to allow communications between the master station and controlling locations (e.g., GSFC/NTTF).

5. An operator I/O console facility is required to allow interaction between operators and the time transfer system. This allows data values such as clock error to be displayed on demand as well as providing a means of entering commands into the system.

3.2.3

The processor system, consisting of a microprocessor and associated peripheral I/O chips, is the basis of the Time Transfer Unit (TTU) hardware and does all required computation and most of the control. In an application where a small amount of simple calculation and a large amount of control are required, a microprocessor is the natural solution. For the time transfer system, the Intel 8080 was initially selected. Other processors (e.g., Zilog's Z-80) have similar capabilities and could also be used. The 8080 was selected because not only does it have a sufficient instruction set, word size, and speed, but also because it is currently well supported by available software, peripheral chips, development hardware, and second-source vendors.

Associated with the microprocessors (μPs) are three types of peripheral interface chips (refer to Fig. 3.1). The USART's are universal synchronous/asynchronous receiver/transmitters which are used to convert the parallel data of the μP into synchronous serial data for the TDRSS transmission link and the reverse for reception. The USART's provide sync words at the start of each data frame during transmission, sync word searching during reception, parity checking if desired, half- or full-duplex operation, and a number of other functions. The USART's also interface naturally with interactive terminal devices (e.g., teletype, CRT console, etc.).

The PPIs are parallel peripheral interfaces which allow direct transfer of parallel data into and out of the μP. Each PPI has the capability of transferring 24 parallel bits. So, for example, to transfer the 40-bit interval measurements, two PPIs are required, leaving 8 bits for control purposes.

Finally, the PIC is a priority interrupt controller which accept external interrupt signals and, in a specified priority, allows one of them to interrupt the μP while holding any others that have occurred. The PIC directs the μP to the processing routine corresponding to the interrupt that was accepted. Hence, the time transfer program operates as an interrupt driven system, making more efficient use of the μP.

3.3 Processor Operation

Functional flowcharts of the master and user systems are given in Fig. 3.2. In general, both master and user processors receive, store, and format the various inputs (e.g., Δ_i's and GMT time) into a data frame. This information is stored in one or more of three tables or buffers. One buffer contains the telemetry to be sent (TX BUFF), another stores the telemetry being received (RX BUFF), and the third retains a history of pertinent data (OLD DATA BUFF). During the kth interval TX BUFF and RX BUFF contain data measured during the (k-1)th interval as well as a running account of the calculated clock error, ϵ, which can be averaged. As part of each interval's calculation phase, the OLD DATA BUFF is updated from the RX BUFF and TX BUFF, and the TX BUFF is updated with new time interval measurements, time-of-day, and a status word.

Each processor will have a simple resident monitor program which allows communication with the I/O console, possibly with NASCOM, aids in debugging, and allows software modifications. Commands to initiate and terminate time transfer could be made by an operator from the console, via the monitor, to the time-transfer program. These commands could also come via NASCOM or be initiated automatically if one so desired. For example, a code lock indication from the TDRSS interface could initiate transfer, and, after a pre-set time (e.g., 30 seconds), the program itself could terminate transfer. There are many possibilities, some of which will prove to be more operationally acceptable than others.

Once initiated, the time transfer program is directed by a series of interrupts which are monitored by the processor's programmable interrupt controller (PIC). Flags can be set to convey certain information required by the program once the data exchange is completed (about 760 msecs into the one-second interval).

The processor is responsible for other activities as well. As the serial data are received by the USART (universal synchronous/asynchronous receiver/transmitter), data validity is checked in various ways. As valid data is accepted and stored, calculations needed to determine clock error are made and checks for End-of-Transmission (EOT) are made.

Finally, following EOT, the processor has the option of performing various kinds of analyses that may be desired and the

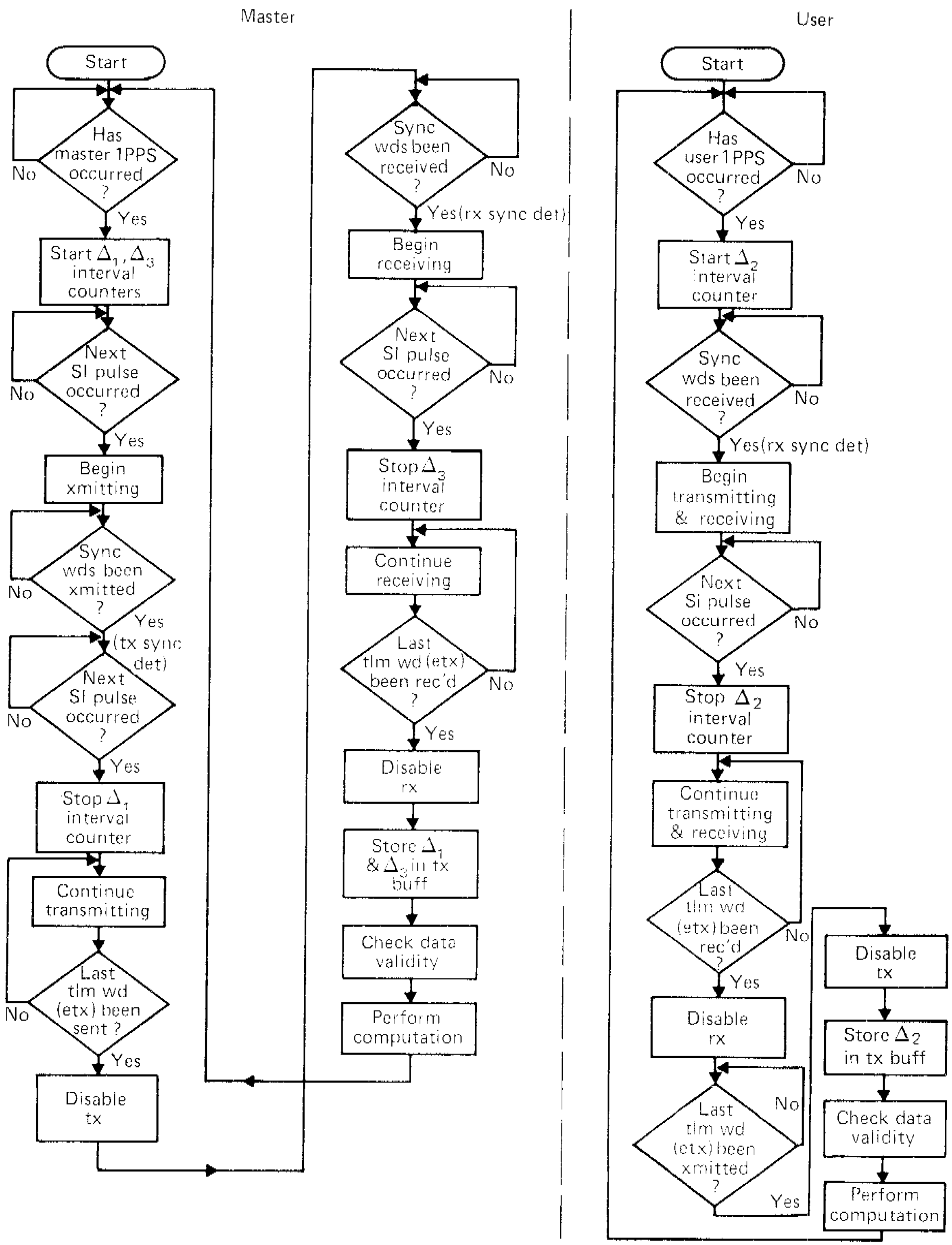


Fig. 3.2 Time Transfer Algorithm – Data Flow Control

capability of displaying requested results on the console or other devices. From there, program control returns to the monitor to await operator commands (either locally via console or remotely via NASCOM).

4.0 TIME TRANSFER ACCURACY

4.1 The TDRSS Relay Path Model

The time interval measurements and clock error calculations which were discussed in Section 2 can be illustrated by the linear model of the TDR satellite relay path shown in Figure 4.1. This linear model assumes that TDR satellite motion results in a constant range rate relative to each station over the time period required for time transfer. The three basic factors which contribute to time transfer error can also be visualized from Figure 4.1. These factors are:

a. The variation in the transmission time or relay path due to both satellite motion and propagation effects. The variation due to TDR satellite motion is a potentially greater source of error if not accounted for than propagation effects.

b. Hardware delays at the TDRSS ground station, the STDN user station, and through the TDR satellite.

c. Variation or "jitter" in the PRN code state indicators (SI's) due to noise in the tracking loops.

The contributions of these factors to the estimate of overall time transfer error is tabulated in Table 4.1 of Section 4.3.

4.2 Calculations Based on the Linear Model

One form of the basic clock error calculation given in Section 2 is:

$$\hat{\epsilon} = \hat{T}_F - (\Delta_2 - \Delta_1) \ . \qquad (4.2\text{-}1)$$

Each of the terms of Eq. (4.2-1) is illustrated on Figure 4.1. The intervals Δ_1 and Δ_2 are measured between a clock one pulse per second (1 pps) and a PRN code state indicator (SI). The forward relay time, T_F, is to be estimated from measurements of the "round trip" relay time, $T_T = \Delta_3 - \Delta_1$, based on the linear model. The estimate of the forward relay time is:

$$\hat{T}_F = \frac{1}{2}\left[1 - \frac{(\gamma_1 + \gamma_2)}{2}\right] T_T + \frac{1}{2}\left(\tau_{FM} - \tau_{RM}\right) \qquad (4.2\text{-}2)$$

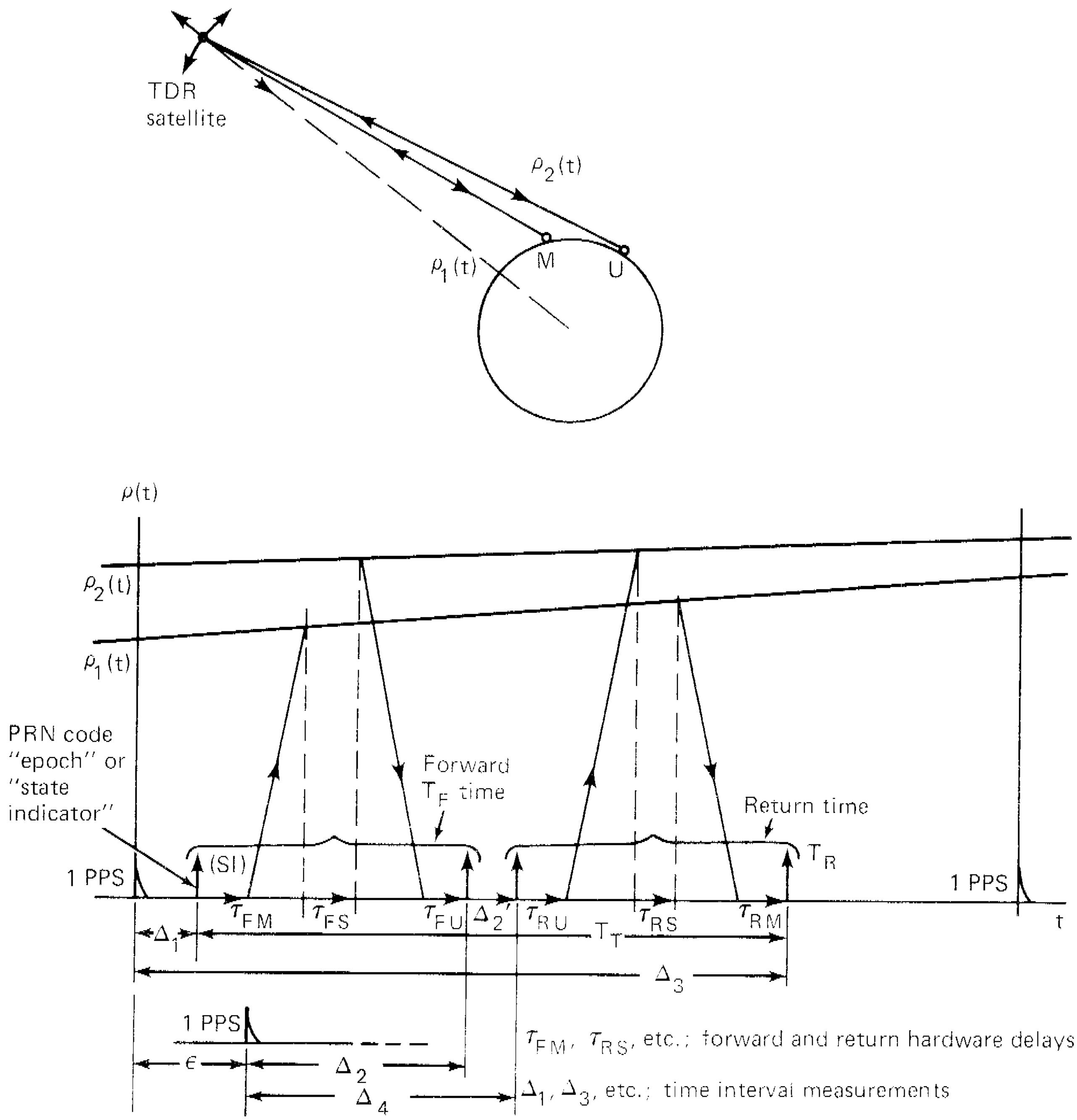


Fig. 4.1 Basic Linear Model of Time Transfer Relay Path

Table 4.1

Error Summary

– Column A assumes currently specified maximum delay variation ($\sim 3\sigma$) for the TDRSS ground station, TDRS Satellite and TDRSS user transponder.

– Column B assumes currently specified "repeatability" of delay variation ($\sim 1\sigma$) for the TDRSS ground station, TDR satellite and TDRSS user transponder.

	Source	Error (A)	Error (B)
1.	Time Interval Measurements and Calculations Based on Linear Model	6 nsec	6 nsec (no avg. or data smoothing)
2.	Differential Delay of STDN Station Hardware (TDRSS Transponder)	30 nsec	10 nsec
3.	Differential Delay at TDRSS Ground Station Hardware	20 nsec	7 nsec
4.	Differential Delay at TDR Satellite	30 nsec	10 nsec
5.	Differential Propagation Effects	~ 1 nsec?	~ 1 nsec?
6.	Total RMS	47 nsec	17 nsec

$$+ \frac{1}{2}(\tau_{FS} - \tau_{RS}) + \frac{1}{2}(\tau_{FU} - \tau_{RU})$$

$$- \frac{\Delta_2'}{2}\left[1 + \frac{1}{2}(\gamma_1 + \gamma_2)\right]$$

$$+ \frac{1}{4}(\gamma_1 + \gamma_2)\left[(\tau_{FM} + \tau_{RM}) - (\tau_{FU} + \tau_{RU})\right]$$

$$- \frac{1}{4}(\gamma_1 - \gamma_2)(\tau_{FS} + \tau_{RS})$$

where $\gamma_1 = \dot{\rho}_1 / v_p$ and $\gamma_2 = \dot{\rho}_2 / v_p$ are the range rate parameters relative to the two stations, e.g., Master and User stations. The velocity of propagation, $v_p = c/n$, with $n \sim 1$ and $c = 2.998 \times 10^8$ meters/sec. A large value of $\gamma_1 + \gamma_2$ for a synchronous satellite orbit is $\gamma \sim 10^{-7}$. As stated in Section 2, this can contribute about a 25 nanosecond bias error over approximately a one minute interval.

Eq. (4.2-2) was derived directly from Figure 4.1 by equating time intervals. Higher order terms in γ, e.g., γ^2, γ^3, etc., are neglected.

The interval Δ_2' at the user, may be a fixed and known PRN code epoch offset, a variable offset requiring measurement, or $\Delta_2' = 0$, implying a "coherent retransmission" of the code received by the user. The delay terms, τ_{FM}, τ_{RM}, etc., refer to the forward and return link delays at the Master, User and TDR satellite.

The rate parameter, $\gamma_1 + \gamma_2$, can be estimated from the time interval measurements as:

$$\widehat{\gamma_1 + \gamma_2} \approx \frac{T_T(t_2) - T_T(t_1)}{t_2 - t_1} = \frac{(\Delta_3 - \Delta_1)_{k+1} - (\Delta_3 - \Delta_1)_k}{1 + (\Delta_{1_{k+1}} - \Delta_{1_k})} \quad (4.2\text{-}3)$$

(A more elaborate "data filter" could be employed to continually update the estimate of both T_T and $\gamma_1 + \gamma_2$, using all the time interval measurements obtained over a period of time.)

Eq. (4.2-2) shows that the hardware delays depicted in Figure 4.1 appear as a differential delay effect, e.g., $\frac{1}{2}(\tau_{FM} - \tau_{RM})$. These differential delays will have to be independently measured or "calibrated out". Accurate ranging via TDRSS also requires knowledge of these delays. Delay measurements for the channels in service will be made as part of normal TDRSS operating procedure. The terms which indicate total hardware delay show either a difference in total delay or are significantly reduced by a differential range rate parameter.

Propagation path delay will also occur as a differential delay between the forward and return paths. Since the forward and return propagation paths are through the same regions of space and the forward and return transmissions occur within a very short time span, the differential delay should be quite small. This should be the case even though the forward and return Ku-band and S-band frequencies are different.

4.3 Time Transfer Accuracy

The linear model discussed in the preceding sections allows the factors which contribute to time transfer error to be categorized. The time interval measurements Δ_1, Δ_2, and Δ_3 which are used in the estimation of forward time, $\hat{T}_F$, the range rate parameters $\gamma_1+\gamma_2$, and the clock error calculation are all subject to noise or "jitter" in the PRN code tracking loops. At the signal margins available for time transfer this tracking jitter would be quite small and averaging (or data filtering based on the linear model) can reduce this contribution even further. The linear model itself should be quite accurate over relatively short intervals, e.g., 10 minutes or so. The time required for forward and return link signal acquisition, data accumulation, and clock error calculation will be about 5 minutes.

Unknown or uncalibrated hardware delay appears to be the largest potential source of time transfer error. Specification data on ground station, satellite and user transponder hardware delay contributions to TDRSS ranging accuracy can be used to estimate time transfer accuracy. These specifications were used to compile Table 4.1 which summarizes the anticipated accuracy of time transfer via TDRSS. Analysis and test data on PRN code tracking stability is used to estimate the effect of jitter. The error summary of Table 4.1 is for "two-way" or "round trip" estimation of forward delay to the user (TDRSS Mode 1).

5.0 SUMMARY OF OPERATIONAL CONSIDERATIONS

If two standard frequencies differ by a few parts in 10^{12} from their nominal frequency of 5 MHz the corresponding clock rate divergence would be about 150 nanoseconds per day or about one microsecond per week. Once a week then, could be a reasonable rate at which to check STDN station clock error. Also, "intensive" test periods of several weeks could be used to establish a "predicted" clock behavior with each stations' clock error being measured twice a day, for example.

5.1 TDRS System Loading

As stated in Section 4.3 the total time transfer interval is expected to be about 5 minutes. This includes forward and return link PRN code and carrier acquisition, data acquisition, and one to two minutes of clock error calculation with sample values occurring at a rate of one per second. The 5 minute interval does not include service configuration time. For example, the time to verify that an assigned Multiple Access (MA) channel is available and operating properly is not included.

If it is assumed that each STDN station's clock error is being checked "regularly", 30 to 40 minutes per week might be required. This would not appear to be a serious operational burden. It was noted in Sections 2.0 and 4.0 that the role of Master and User stations could be interchanged so that the error of the TDRSS ground station clock could also be checked as a routine procedure.

5.2 Forward Beam Sharing

Since the Multiple Access (MA) service is to have 20 return channels per TDR satellite (potential total of 3x20=60 channels) but only one forward channel per TDR satellite (a total of 3) it will be the forward link accessibility that places whatever limitations might arise on time transfer via TDRSS Mode 1 operation. This mode is the two-way "coherent ranging" mode which permits estimation of the forward propagation time by the "round trip" measurements discussed in Section 4.2. Since the MA forward antenna beam is relatively broad, i.e., about 10°, the possibility of several time transfer users sharing the same forward beam exists and will be considered as an operational possibility. Sharing a forward beam would permit clock error estimates to be made for several STDN stations in rapid succession. This approach would require additional time transfer signal multiplexing in the processor/controller.

5.3 "One-Way" Time Transfer Accuracy

The basic technique and hardware discussed in Sections 2 and 3 and the model described in Section 4.1 permit clock error calculation either by forward-link-only transmission from the TDRSS ground station to the STDN user station or by return-link-only (TDRSS Mode 2) from the STDN user station to the TDRSS ground station. The fundamental difference is that for these "one-way" transmissions, the estimate of forward propagation time $\hat{T}_F$ (or $\hat{T}_R$) required for the clock error calculation must be obtained from TDR satellite ephemeris data rather than a "round trip" delay measurement. Hardware and propagation delays affect the error calculation directly, not as a delay difference as in the "two-way" transmission case. The accuracy available with return-link-only or forward-link-only transmission should be in the order of 600 nanoseconds depending upon the validity of TDR satellite orbit predictions for the time period over which the clock error is being estimated. As noted in Section 1.5, one purpose of the TDRS user transponder at the STDN stations is for the support of TDR satellite orbit determination by "bilateration ranging". This support will contribute to the accuracy of time transfer to a STDN station when the transponder is used for that purpose in a "one-way" transmission mode.

QUESTIONS AND ANSWERS

DR. GART WESTERHOUT, U. S. Naval Observatory:

Five speakers described satellite time transfer systems, all of them different but all of them doing the same thing. Is there a movement afoot to eventually standardize some of this?

MR. McINTYRE:

I'm not aware of any such efforts. The TDRS system is really to be part of the NASA Tracking and Data Network in the 1980's, and it is satisfying NASA purposes in supporting space missions of all varieties--the space shuttle, for example. It turns out that the particular signal design and implementations we have discussed here are very suitable to transferring time to the ground stations of that network. There is no attempt to duplicate or not duplicate what someone else is doing. It is here--we will use it.

MR. ROGER EASTON, Naval Research Laboratory:

Let me answer a little differently. Paper 11 had 100 microseconds as far as accuracy. Paper 12 was 25 microseconds, and paper 14 was about 100 nanoseconds. So there is quite a difference in the accuracy of several of the systems.