NASA TECHNICAL NOTE **NASA TN D-8073**

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AN ANALYSIS OF SPACECRAFT DATA TIME TAGGING ERRORS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1975

1. Report No.
TN D-8073

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
An Analysis of Spacecraft Data
Time Tagging Errors

5. Report Date
September 1975

6. Performing Organization Code
565

7. Author(s)
Ai Chun Fang

8. Performing Organization Report No.
G-7607

9. Performing Organization Name and Address
Goddard Space Flight Center
Greenbelt, Md. 20770

10. Work Unit No.

11. Contract or Grant No.
311-07-01-68

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Note

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

In the operation of spacecraft and the experiments they carry, and in spacecraft tracking and analysis of the data obtained, the precise time at which events in space occur is needed. In spite of the sophistication of most timing and telemetry systems, these precise times are still an elusive quantity because of the need to process a large quantity of data in a very short time and also because of the small errors built into most telemetry systems.

A precision study of many timing/telemetry systems would be of value but would require an inordinate amount of time. This study, an indepth examination of the timing and telemetry in just one spacecraft, points out the genesis of various types of timing errors and can serve as a guide in the design of future timing/telemetry systems.

The principal sources of timing errors are examined carefully and are described in detail. Estimates of these errors are also made and presented. It is found that the timing errors within the telemetry system are larger than the total timing errors resulting from all other sources.

17. Key Words (Selected by Author(s))
Computers, Electronic equipment,
Communications, Telemetry, RF systems

18. Distribution Statement
Unclassified—Unlimited
Cat 17

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
30

22. Price*
$3.75

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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NOTATION

AGC	Automatic gain control
A_r	Aging rate of station clock
A_t	Actual time of spacecraft clock
BCD	Binary coded decimal
BIH	Bureau International de l'Heure
B_P	Bit period ($B_P = 1/B_r = 1.018$ ms for normal operation)
B_r	Bit rate ($B_r = 981.4453125$ bps for normal operation)
C	The speed of light
$\bar{D}$	Vector of the slant range with magnitude D
D_t	Measured time difference between the station clock and the received Loran-C pulse
E_c	Station clock error
E_{ev}	Error in event time
E_{FR}	Frame rate error
E_{Lev}	Limit of E_{ev}
E_{LFR}	Limit of E_{FR}
E_r	Loran-C correction term
E_{sc}	Apparent spacecraft clock time error ($E_{sc} = 1.9562986$ s)
$(F_E)t_0$	Initial frequency error of station clock

NOTATION *(continued)*

GRP	Group repetition period
ITBE	Interchannel time base error
J_n	Total jitter
ℓ	Number of times sampled
M_F	Major frame time ($M_F = 212.84528$ s)
m_R	Minor frame time ($m_R = 0.83143$ s)
n	An integer
$\overline{P}$	Spacecraft position vector with magnitude P
P_d	Propagation delay
P_s	The period of the spacecraft clock ($P_s = 1.9562986$ s)
P_x	The components of P
P_y	
P_z	
$\overline{S}$	The station's position vector with magnitude S
SD	Serial decimal
S_x	The components of S
S_y	
S_z	
t_A	Spacecraft apparent clock time
T_a	Time between consecutive pulses

NOTATION *(continued)*

T_{av}	Exact event time
TBE	Time base error
T_{ER}	Time error of station clock
T_{n+1}	Time at which (n+1)*th* pulse starts
T_{ev}	Apparent event time
$(T_E)t_0$	Initial time error of station clock
T_p	Propagation time
t_s	Time interval
T_T	Time at which data signal is telemetered to earth
UT	Universal time
UTC	Coordinated universal time

AN ANALYSIS OF SPACECRAFT DATA TIME TAGGING ERRORS

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INTRODUCTION

In spacecraft tracking and space phenomena experimentation, there is a need to determine the exact time at which various events occur. Because a majority of the space data use time as an independent variable, accuracy of time becomes a great concern to both scientists and engineers.

The telemetry system studied was that of the Small Astronomy Satellite-C (SAS-C) spacecraft, which contains fairly typical timing and telemetry systems. These systems are used to collect experimental data and to generate spacecraft clock time with onboard instruments. The coordinated universal time (UTC) is obtained in conjunction with data from the ground network tracking station. The time and experimental data are processed through analog-to-digital conversion at the Information Processing Division (IPD) of Goddard Space Flight Center (GSFC). Because there is a series of operations and procedures involved, it appears that a certain number of errors in timing is unavoidable. These timing errors are due to equipment delay, factors of uncertainty, high resolution of timing device, and the limited ability of the telemetry system.

This document presents the study of minute but accumulative timing errors in the telemetry system of the SAS-C spacecraft. Obviously, the results are applicable to other spacecraft. Timing errors caused by malfunction of electronic circuitry or components, improper operation, or careless mistakes are unpredictable and are not considered in this study.

Because reference and test data for determining the number of timing errors in the telemetry system were not available, a survey was made to obtain information from space engineers, scientists, data analysts, and data processing engineers. Their points of view and their estimates of timing errors in each related step of the telemetry system are considered here.

TELEMETRY SYSTEM

Three major parts in the telemetry system handle experimental data from its collection in the spacecraft to final delivery to the experimenters. A block diagram of the telemetry system is shown in figure 1. The three major parts are as follows:

- Spacecraft instrumentation
- Ground network tracking stations
- Central information processing facility

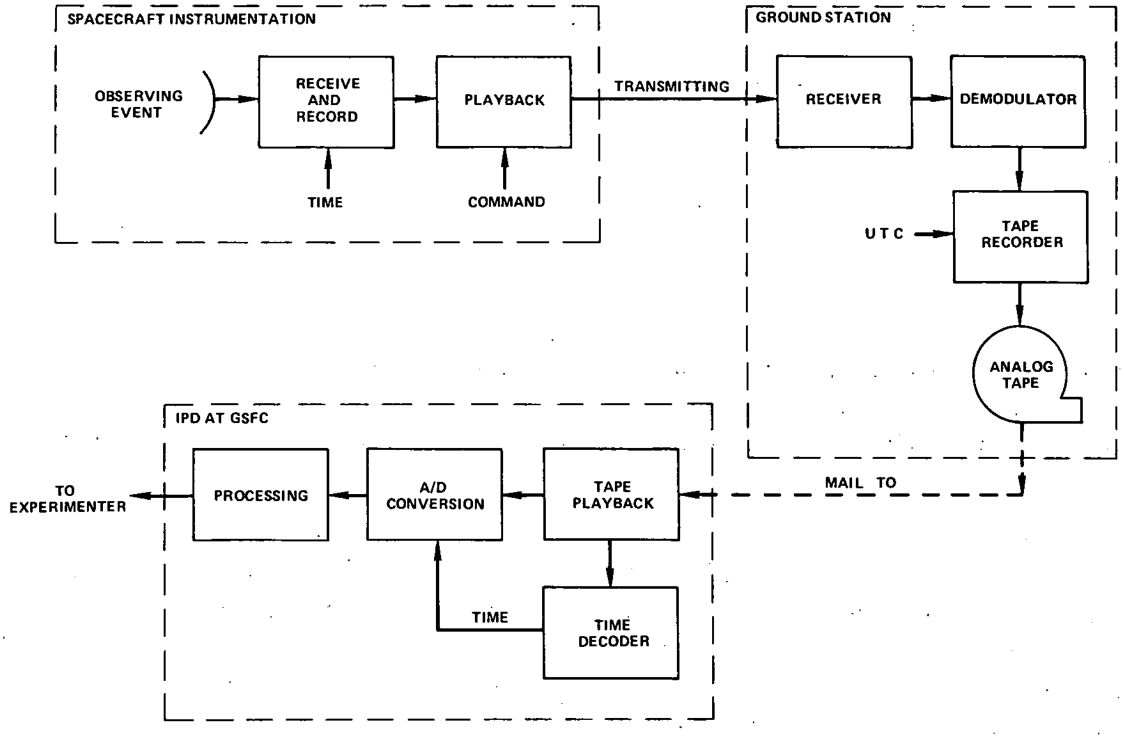

Figure 1. Block diagram for telemetry system.

The instruments on board the spacecraft detect the events, collect the data, generate time counts, and transmit all information to the earth by means of radio signal modulated by telemetry data of known format. The ground network stations are equipped with antennas and receivers to receive the telemetry message. A station clock provides UTC. A time encoder is used at ground stations to produce a time code, which is a time base synchronized with UTC and which indicates the data reception time at the receiving station. The time code is then serially recorded on a channel of analog magnetic tape adjacent to the channel on which the incoming space data are being recorded. The analog tapes produced at the ground stations are shipped to the central information processing facility at GSFC.

After the tapes arrive at the processing facility, a series of operations immediately follows: The tapes are evaluated to ensure the quality. A time decoder is used to decode the time and detect the errors. The analog data are simultaneously converted to digital form in the analog-to-digital conversion equipment. The digital data are then recorded on a digital magnetic tape which subsequently is edited and decommutated. This brief description of a telemetry system is typical of the majority of spacecraft.

Over the years, a great deal of effort has been made at GSFC to correct the timing errors associated with telemetry space data. However, timing problems occur in each new project. This is because each spacecraft has a different design for the electronic circuitry and its associated instruments. Timing errors in each case require special techniques for detection and correction. This includes the errors which can originate in the spacecraft instrumentation, in addition to the equipment in ground network stations and the central information processing facility.

The spacecraft instrumentation studied incorporates an onboard clock, a timing device, two onboard tape recorders for data storage, and two transmitters for signal transmission. It also contains two format generators, two multiplexers, and two encoders. The format generator accepts the prime input from 64 separate sources and generates appropriate signals according to a prescribed telemetry format. The multiplexer uses these signals and combines them serially into proper sequence. These data are then sent to the encoder where they are converted to split phase wave form. Output from the encoder goes to tape recorders or to the transmitters through premodulation filters.

In order to ensure the return of experimental data, certain parts of the telemetry system are redundant; that is, there are two identical units such as tape recorders, multiplexers, and encoders. The RF link redundancy is provided by a UHF transmitter and an S-band transmitter. The format generator redundancy is obtained by having a fixed format generator and a variable format generator.

SPACECRAFT CLOCK

Because the clocks are fundamental devices for measuring time, any possible error can be partially attributed to the clocks. Due to the results of inherent instability and environmental effects, two clocks which operate properly and which have been initially synchronized will eventually indicate different times. Recently, spacecraft clock design has been considerably advanced. The requirements for onboard spacecraft clocks indicate that they must be ultrastable and nonstop during playback. The timing source for SAS-C consists of a crystal controlled oscillator, which contains completely redundant crystals and their associated circuitry. The crystal oscillator produces a 5.025-MHz signal with a clock output period of 1.9562986 seconds. The signal is used to input the binary divider and to synthesize the required clock rates for the telemetry subsystem. Each divider chain is capable of accepting the input signal, generating the assigned frequencies, and providing data transfer clock output to all subsystems.

A block diagram of the spacecraft clock and telemetry system is shown in figure 2. The spacecraft clock contains the time code generator which relates spacecraft time to ground time. The time code generator is a 24-bit binary counter, which counts the oscillator's signal with the rate of one count per 1.9562986 seconds. The signal counts are a constant numerical sequence, in synchronization with the flow of space data in the telemetry system. The time code generator possesses the capability of a nonrepeating readout for approximately one year if power is not removed.

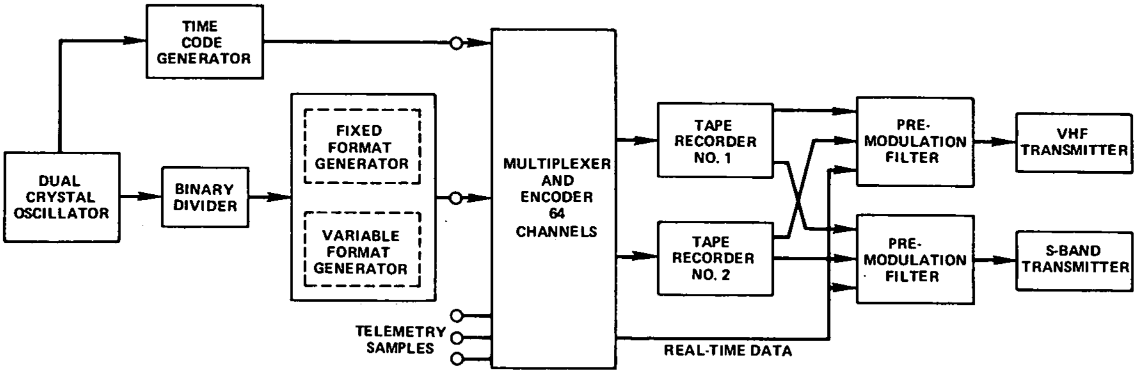

Figure 2. Spacecraft clock and telemetry system.

An environmental effect such as temperature can cause the oscillator to drift. Thus, when the spacecraft enters the sunlit portion of the orbit, the clock will run faster than when it is in the earth's shadow. However, the design of the crystal oscillator has the crystals cut in a direction such that the temperature effect is reduced to a minimum. In addition, very accurate temperature control is provided by completely redundant proportional-controlled heaters. The oscillator is thus kept at the same temperature by temperature-sensing devices which eliminate the effect caused by temperature changes.

Usually a clock on board the spacecraft experiences the magnetic field effect and the relativistic effect. The magnetic effect is due to the result of the earth's magnetic field and the local magnetic field, especially when the spacecraft passes through a region where the field strength changes rapidly. The relativistic effect is due to the rate of change in range relative to the observer. Normally, both effects can alter the clock behavior. Because the clock on board the spacecraft studied is well shielded, the magnetic effect is considered negligible so far as clock drift is concerned. Because of the slow speed of the spacecraft with respect to the ground observer, the relativistic effect is minimal and can also be neglected.

The spacecraft clock stability is one part in 10^{10} per orbit. The clock itself is stable, yet it can do very little in determining the actual time of the telemetry data.

TELEMETRY DATA

All telemetry data in the spacecraft are the result of observations and measurements of scientific or engineering phenomena throughout the celestial sphere. These observations and measurements are sampled sequentially during a specific time interval as shown in figure 3. Each repetition of the sampling sequence is a telemetry frame which consists of analog or digital data measurements at regular intervals.

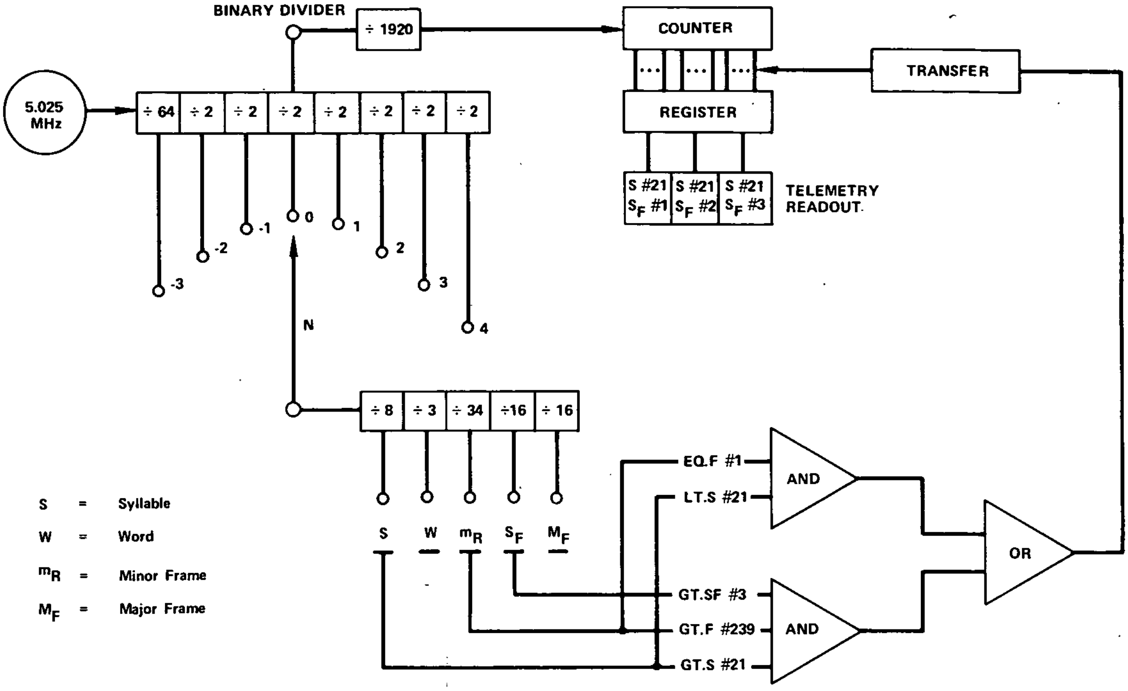

Figure 3. Spacecraft clock and telemetry data flow.

Frame identification is determined by a binary frame counter, which defines the length of each major frame and minor frame. Each major frame is defined to be a complete sequence of 256 minor frames, and each minor frame contains 34 words with 24 bits per word for a total of 816 bits. Measurements of experiment data are located in the same relative positions in each frame. Besides the experiment data words, each minor frame has a 24-bit frame synchronization for its first word, an 8-bit format identification for the third portion of its second word, and a word of frame counter value. (See figure 4.)

The spacecraft clock time, expressed in a 24-bit word, is placed at the start of each major frame and is contained in the first 3 of each 16 minor frames. The spacecraft clock time is read out once each 16 minor frames. The 24-bit word of clock time is divided into 3 parts with 8 bits per part. Each 8-bit part is placed in the third portion of word No. 22 to fill the content of "DSC No. 1"* in the first 3 minor frames in a group of 16 minor frames. The rest of the minor frames in this group will not contain the spacecraft clock time again until the first 3 frames of the next 16-minor-frame group. This can be seen from table 1 and figures 4 and 5.

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*Note that "DSC No. 1" is digital subcommutator number one.

<table>
<tr><th rowspan="2">WORD</th><th colspan="6">BITS</th></tr>
<tr><th colspan="6">2 4 6 8 10 12 14 16 18 20 22 24</th></tr>
<tr><td>0</td><td colspan="6">FRAME SYNCHRONIZATION</td></tr>
<tr><td>1</td><td colspan="2">FORMAT NO.</td><td colspan="2">PARITY</td><td colspan="2">FRAME I. D.</td></tr>
<tr><td>2</td><td colspan="3">CHANNEL 2</td><td colspan="3">CHANNEL 3</td></tr>
<tr><td>3</td><td colspan="3">CHANNEL 2′</td><td colspan="3">CHANNEL 3′</td></tr>
<tr><td>4</td><td colspan="3">CHANNEL 2</td><td colspan="3">CHANNEL 3</td></tr>
<tr><td>5</td><td colspan="2">CHANNEL 4</td><td colspan="2">CHANNEL 11</td><td colspan="2">CHANNEL 5</td></tr>
<tr><td>6</td><td colspan="6">CHANNEL 9 (ASPECT 1)</td></tr>
<tr><td>7</td><td colspan="3">CHANNEL 6</td><td colspan="3">CHANNEL 7</td></tr>
<tr><td>8</td><td colspan="3">CHANNEL 2′</td><td colspan="3">CHANNEL 3′</td></tr>
<tr><td>9</td><td colspan="2">CHANNEL 4′</td><td colspan="2">ASCO(APL HK)</td><td colspan="2">CHANNEL 5′</td></tr>
<tr><td>10</td><td colspan="3">CHANNEL 6′</td><td colspan="3">CHANNEL 6</td></tr>
<tr><td>11</td><td colspan="3">CHANNEL 7′</td><td colspan="3">CHANNEL 7</td></tr>
<tr><td>12</td><td colspan="6">CHANNEL 10 (ASPECT 2)</td></tr>
<tr><td>13</td><td colspan="2">CHANNEL 4</td><td colspan="2">DSC NO. 0</td><td colspan="2">CHANNEL 5</td></tr>
<tr><td>14</td><td colspan="3">CHANNEL 1</td><td colspan="3">CHANNEL 1′</td></tr>
<tr><td>15</td><td colspan="3">CHANNEL 1</td><td colspan="3">CHANNEL 8</td></tr>
<tr><td>16</td><td colspan="3">CHANNEL 2</td><td colspan="3">CHANNEL 3</td></tr>
<tr><td>17</td><td colspan="3">UNASSIGNED</td><td colspan="3">CHANNEL 1′</td></tr>
<tr><td>18</td><td colspan="2">CHANNEL 4′</td><td colspan="2">ASCI (EXP HK)</td><td colspan="2">CHANNEL 5′</td></tr>
<tr><td>19</td><td colspan="3">CHANNEL 2′</td><td colspan="3">CHANNEL 3′</td></tr>
<tr><td>20</td><td colspan="3">CHANNEL 2</td><td colspan="3">CHANNEL 3</td></tr>
<tr><td>21</td><td colspan="3">CHANNEL 2′</td><td colspan="3">CHANNEL 3′</td></tr>
<tr><td>22</td><td colspan="2">CHANNEL 4</td><td colspan="2">CHANNEL 11′</td><td colspan="2">DSC NO. 1</td></tr>
<tr><td>23</td><td colspan="6">CHANNEL 9′ (ASPECT 1)</td></tr>
<tr><td>24</td><td colspan="3">CHANNEL 6′</td><td colspan="3">CHANNEL 7′</td></tr>
<tr><td>25</td><td colspan="3">CHANNEL 2</td><td colspan="3">CHANNEL 3</td></tr>
<tr><td>26</td><td colspan="2">CHANNEL 4′</td><td colspan="2">ASC2 (APL HK)</td><td colspan="2">CHANNEL 5</td></tr>
<tr><td>27</td><td colspan="3">CHANNEL 6</td><td colspan="3">CHANNEL 6′.</td></tr>
<tr><td>28</td><td colspan="3">CHANNEL 7</td><td colspan="3">CHANNEL 7′</td></tr>
<tr><td>29</td><td colspan="6">CHANNEL 10′ (ASPECT 2)</td></tr>
<tr><td>30</td><td colspan="2">CHANNEL 4</td><td colspan="4">TLM VERIFICATION</td></tr>
<tr><td>31</td><td colspan="3">CHANNEL 8′</td><td colspan="3">CHANNEL 8</td></tr>
<tr><td>32</td><td colspan="3">CHANNEL 1</td><td colspan="3">CHANNEL 8′</td></tr>
<tr><td>33</td><td colspan="3">CHANNEL 2′</td><td colspan="3">CHANNEL 3′</td></tr>
</table>

Figure 4. SAS-C telemetry minor frame format, experiment mode A.

<table>
<tr><th rowspan="2">WORD</th><th colspan="6">BITS</th></tr>
<tr><th>2 4</th><th>6 8</th><th>10 12</th><th>14 16</th><th>18 20</th><th>22 24</th></tr>
<tr><td>0</td><td colspan="6">FRAME SYNCHRONIZATION</td></tr>
<tr><td>1</td><td colspan="2">FORMAT NO.</td><td colspan="2">PARITY</td><td colspan="2">FRAME I.D.</td></tr>
<tr><td>2</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>3</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>4</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>5</td><td colspan="2">CHANNEL 11</td><td colspan="2">CHANNEL 11</td><td colspan="2">CHANNEL 5</td></tr>
<tr><td>6</td><td colspan="6">CHANNEL 9 (ASPECT 1)</td></tr>
<tr><td>7</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>8</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>9</td><td colspan="2">CHANNEL 11'</td><td colspan="2">ASC0 (APL HK)</td><td colspan="2">CHANNEL 5'</td></tr>
<tr><td>10</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>11</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>12</td><td colspan="6">CHANNEL 10 (ASPECT 2)</td></tr>
<tr><td>13</td><td colspan="2">CHANNEL 11'</td><td colspan="2">DSC NO. 0</td><td colspan="2">CHANNEL 5</td></tr>
<tr><td>14</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>15</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>16</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>17</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>18</td><td colspan="2">CHANNEL 11</td><td colspan="2">ASC1 (EXP HK)</td><td colspan="2">CHANNEL 5'</td></tr>
<tr><td>19</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>20</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>21</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>22</td><td colspan="2">CHANNEL 11'</td><td colspan="2">CHANNEL 11'</td><td colspan="2">DSC NO. 1</td></tr>
<tr><td>23</td><td colspan="6">CHANNEL 9' (ASPECT 1)</td></tr>
<tr><td>24</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>25</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>26</td><td colspan="2">CHANNEL 11</td><td colspan="2">ASC2 (APL HK)</td><td colspan="2">CHANNEL 5</td></tr>
<tr><td>27</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>28</td><td colspan="3">CHANNEL 11</td><td colspan="3">CHANNEL 11</td></tr>
<tr><td>29</td><td colspan="6">CHANNEL 10' (ASPECT 2)</td></tr>
<tr><td>30</td><td colspan="2">CHANNEL 11'</td><td colspan="4">TLM VERIFICATION</td></tr>
<tr><td>31</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>32</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
<tr><td>33</td><td colspan="3">CHANNEL 11'</td><td colspan="3">CHANNEL 11'</td></tr>
</table>

Figure 5. SAS-C telemetry minor frame format, experiment mode B.

Table 1
Digital Subcommutators Channel Allocation

Channel		Digital Subcommutator No. 0
S	0	Charge regulator and monitor (CRAM) status
S	1	CRAM battery ampere-minutes discharge
S	2	Spare
S	3	Spare
P	4	Momentum wheel speed monitor
P	5	Momentum wheel speed monitor
P	6	Momentum wheel speed monitor
P	7	Command verification
P	8	Command verification
P	9	Command verification
P	10	Command verification
P	11	Command verification
P	12	Command verification
P	13	Command verification
P	14	Command verification
P	15	Spare
		Digital Subcommutator No. 1
P	0	Time code generator
P	1	Time code generator
P	2	Time code generator
S	3	Nutation damper angle
S	4	Attitude system verification
S	5	Spare
S	6	Spare
P	7	Telemetry rate and digital solar attitude detector (DSAD) status
S	8	Nonspinning DSAD A angle
S	9	Nonspinning DSAD B angle
S	10	Spinning DSAD angle
P	11	MSBs* of time (spinning DSAD)
P	12	LSBs† of time (spinning DSAD)
S	13	Experiment data command status verification
S	14	Experiment data command status verification
S	15	Experiment data command status verification

Notes:

MSB* LSB†
Each channel is interpreted as follows: X X X X X X X X
B0 B7

MSB* or B0 is the first bit shifted into the data stream.

S indicates that 8 bits of non-return-to-zero (NRZ-C) data are accepted serially.

P indicates that 8 bits of data are converted from parallel to serial NRZ-C.

* Most significant bit

† Least significant bit

The time interval between major frames and the time interval between minor frames are constants and are defined as the major frame time M_F and the minor frame time m_R. Their values depend on the bit rate B_r. For normal operation, the bit rate is

$$B_r = 981.4453125 \text{ bps.}$$

It is understood that this bit rate value is used most of the time as the spacecraft is orbiting the earth. The major frame time and the minor frame time are therefore computed as follows:

$$M_F = 256 \times \frac{816}{981.4453125} = 212.846528 \text{ s}$$

$$m_R = \frac{816}{981.4453125} = 0.83143 \text{ s.}$$

ERRORS IN SPACECRAFT CLOCK TIME

Because the period of the spacecraft clock time, P_s, is 1.9562986 seconds, it follows that

$$P_s = 2.35 \, m_R$$

or

$$m_R = 0.425 \, P_s$$

and

$$M_F = 108.8 \, P_s.$$

Because the value of P_s is neither a multiple of m_R nor equal to m_R, there is a problem concerning the time accuracy. Because the clock is read out only once every 16 minor frames instead of once per minor frame, the problem becomes more difficult. In fact, the spacecraft clock time, which is either shown in the first word of every major frame or shown in the first three minor frames of a 16-minor-frame group, does not indicate the exact time that the time count occurs. The time count may have occurred earlier at any moment within the past 1.9562986 seconds and may wait to be combined serially with other space data until it accumulates to fill certain positions of assigned frames. The spacecraft clock time shown in any major frame or in any three minor frames is defined as the apparent spacecraft clock time, t_A, which could be different from the actual time, A_t, at which the spacecraft clock sends its output time signal. The difference between them is the apparent spacecraft clock time error, E_{sc}, where

$$E_{sc} \leqslant 1.9562986 \text{ s.}$$

That is, if the value of t_A is taken to be the actual space clock time, the error in time may be as large as 1.956298 seconds. In fact, there is no way to determine the value of actual time, A_t, if the obtained telemetry data is the only available information. As a result, the minor frame time, m_R, may be the only value to be used for reference of spacecraft clock time.

By using the reference m_R as a new time base, the time of any observational data that appear in a position of a minor frame can be obtained by interpolation. Time so obtained is defined as the apparent event time and is denoted by T_{ev}. The symbol T_{av} represents the exact time at which the spacecraft observes the event. Then T_{ev} is not equal to T_{av}, the difference between these two values being called the error in the event time and represented by E_{ev}. If that observational data is only sampled once every minor frame, then

$$T_{ev} - T_{av} = E_{ev} \leqslant m_R = 0.83143 \text{ s.}$$

It is very difficult to determine the value of the exact event time, T_{av}, at which the event occurs, because the event may happen at the moment when its data is too late to be placed on the assigned position in the previous minor frame and is too early to fill the same position in the coming minor frame. Thus, the assumption that apparent event time is the exact time of event occurrence may result in an error, E_{ev}, to a value less than or equal to 0.83143 second. This error in timing is not uniform and is not easy to notice. It cannot be corrected on the ground since it is caused by the spacecraft telemetry system itself.

If the limit of E_{ev} is E_{Lev}, then

$$E_{Lev} = m_R = \frac{816}{B_r} \quad .$$

The limit of the error in event time is thus inversely proportional to the bit rate; E_{Lev} increases when B_r decreases, or vice versa. Because the spacecraft has the ability to vary the bit rate upon command, the change of the E_{Lev} value immediately follows. The variable bit rate is expressed as

$$B_r = 981.4453 \times 2^N \text{ bps}$$

where N = -3, -2, ... 3, 4.

The corresponding value of E_{Lev} is therefore

$$E_{Lev} = 0.83143 \times 2^{-N} \text{ s.}$$

Time Error and Attitude Determination

The error in the event time which originates in the spacecraft telemetry system is often neglected or unnoticed because the time accuracy might not seem important in some experimental data, and the timing errors caused by the system design are therefore ignored. It should be pointed out that, in most cases, the timing errors directly affect the experimental result. Improved design of the telemetry systems in most spacecraft can eliminate the errors in the spacecraft clock time and the errors in the event time. For example, if the spacecraft contains a star sensor, the transit times of stars are required to be accurate to within a few milliseconds. This is because the transit times are used to identify the stars, in order to determine the attitude of the spacecraft. If the spacecraft telemetry system has built-in timing errors, each transit time recorded is not the instant at which the star is centered in the sensor slit. The telemetry data of transit time has automatically contained the error in event time, E_{ev}, of much more than a few milliseconds; therefore, the attitude determination can never obtain the required accuracy. As a result, the difficulty in matching the stars arises, and the stars may be given incorrect identifications. Under these conditions, the attitude of the spacecraft can hardly be determined correctly, even though there is a very good star sensor on board the spacecraft to observe the star and to produce the correct star transit pulse. It is impossible to improve the attitude solution, except when simulated transit data are used as a substitute for the real telemetry star transient data. Evidently the accurate solution is based on the correct data, and the correct telemetry data depend on the proper design of the spacecraft telemetry system.

A Consideration of Error Reduction

The error in the spacecraft clock time is directly proportional to the spacecraft clock period, and this error can be reduced by lowering the period of the spacecraft clock. For instance, if the spacecraft clock has a period of 0.1 second, the error of the spacecraft clock time is within 0.1 second. This error also can be decreased when the spacecraft clock time is sampled once every 0.1 second, even though the clock period is not changed. Similarly, the error limit of the event time can also be reduced if the minor frame time is lowered when the bit rate is unchanged. If the minor frame time, m_R, is lowered from 0.83 second to 0.15 second, the error in the event time is immediately limited to less than 150 ms.

It should be noted that the value of E_{ev} can be decreased by sampling the observation data more frequently in each minor frame. For instance, if the observation data are sampled four times per minor frame, the error E_{ev} is reduced to

$$E_{ev} \leqslant \frac{m_R}{4} = 0.207857 \text{ s.}$$

The disadvantage caused because the spacecraft clock period is synchronized with neither the minor frame time nor the major frame time becomes very obvious. The fact that the value of the spacecraft time counter is sampled once in 212.84608 seconds presents obstacles to trace the exact time of the time signal count. The clock's function is thus limited by the design of the telemetry to such a degree that the clock has no chance to use its precision. In this case, it really makes no difference whether the onboard spacecraft clock has the desired precision or not. Nevertheless, the space clock can be allowed an important role in timing the telemetry data if its period, P_s, is synchronized with the minor frame time, m_R. This can be done by changing the period of the clock time from its original value of 1.956298 to 0.83143 second. Such a change will provide the advantages that the actual clock signal count is much easier to know and the clock time error, E_{sc}, is limited to a much smaller value. Besides, the time counter can also serve as a minor frame counter. Thus, the time counter can eliminate the need for a minor frame counter, reducing the cost of building one and saving room in the spacecraft.

DATA STORAGE AND TRANSMISSION

The telemetry system has two modes of operations: real-time mode and playback mode. The real-time mode records the space data and transmits the real-time data. The playback mode plays back the stored data. The real-time data contain telemetry data obtained during contact with the ground station, and the stored data contain telemetry data recorded previously in the spacecraft tape recorder.

The two continuous loop tape recorders used on SAS-C were built by GSFC for onboard data storage. Each tape recorder accepts split phase coded data directly from the encoder and can store 6×10^6 bits on a single track of the tape. For a nominal rate of 981.4453125 bps, each recorder is capable of recording input data for 100 minutes to get 100-percent orbital coverage.

The spacecraft communicates with the ground station by means of transmitting real-time data or playback data. The transmission is carried out by a VHF and an S-band transmitter. Both transmitters are phase modulated by split phase encoded data. Each transmitter possesses two different power levels: a high power level used for transmitting playback data and a low power level for real-time data. Both transmitters can be operated simultaneously with real-time data transmitted on one transmitter and playback data transmitted on the other.

Because ground station access time is possible during small portions of an orbit, the playback mode must transmit at high speeds. Upon receiving a playback command from a ground station, the data which were recorded on previous orbits are played back at a speed which is 20 times the record speed. With the nominal playback rate of 19628.890625 bps, the recorded contents for one full orbit are transmitted in approximately 5 minutes. While the data are played back for transmission by one recorder, the real-time data can be recorded on the other recorder to preserve all experimental data. When the complete readout of the magnetic tape is reached, the tape recorder issues a signal to indicate the end of the playback and automatically returns to real-time mode.

There is a time delay between receiving a signal message and placing it on storage in the onboard tape recorder. According to estimates from space engineers, this delay is less than 50 μs. When a pulse code modulated (PCM) signal from the encoder or from either of the onboard tape recorders phase modulates the transmitter, there is also a delay between the signal pulse triggering the transmitter and the RF signal occurring at the output. This delay is called transmitter delay, which will be included in the signal propagation time.

BIT PERIOD AND ERROR-IN-FRAME RATE

For normal operation, the bit rate, B_r, for the real-time mode is 981.4453125 bps; that is the nominal bit rate at which data can be recorded on the spacecraft tape recorder. It is also the bit rate at which real-time data are transmitted to the ground stations. The bit period, B_P, which is defined as the time interval that each bit requires, can be calculated as

$$B_P = \frac{1}{B_r} = \frac{1}{981.4453125} = 1.018 \ \mu\text{s}.$$

Each bit requires the nominal value of 1.018 ms to complete the operation of real-time mode; therefore, there is an uncertainty associated with this bit period because it is not known when each bit is sampled. The time for sampling each bit can begin at any moment within the 1.018 ms. There are 208,896 bits in one major frame, and, because of noise or some other unexpected reason, it is very possible that any one bit could be sampled earlier or later than its usual time. If this occurs, all following bits are affected and the error in frame time appears. For example, if one bit is sampled early and completes its bit period about 0.1 ms in advance, then that particular bit immediately disturbs the others and forces them to take the same step. Consequently, the major frame and the minor frame which contain that bit have a frame time that is 0.1 ms less than its prescribed value. Similarly, if one bit is sampled much later than its expected time, both the major frame and minor frame to which that particular bit belongs have longer frame rates. It is reasonable to conclude that neither the major frame time nor the minor frame time is absolutely constant. The frame time is therefore varied, and the variation is quite small and not uniform. However, the average frame time is expected to approach the assigned prescribed value.

The probable error in the frame time (either major frame or minor frame) could be as large as the uncertainty of the starting time for each bit to be sampled. In general, this uncertainty is taken as one-tenth of the bit period. If E_{FR} is the frame time error, then

$$|E_{FR}| \leq \frac{B_P}{10} = 0.102 \text{ ms}.$$

The bit period varies whenever the bit rate is changed, because the bit period depends on the value of the bit rate. The various values of bit period can be computed by

$$B_P = \frac{1}{981.4453 \times 2^N} = 1.018 \times 2^{-N} \text{ ms}$$

where N = -3, -2, ..., 3, 4.

The corresponding major frame time and minor frame time are, respectively,

$$M_F = 112.84608 \times 2^{-N} \text{s}$$

and

$$m_R = 0.813143 \times 2^{-N} \text{s.}$$

The error in the frame time can be expressed by the following relationship:

$$|E_{FR}| \leqslant 0.102 \times 2^{-N} \text{ ms.}$$

For each N, the error in the frame time lies between 0 to 0.102×2^{-N} ms. The value of 0.102×2^{-N} ms may be represented by E_{LFR}, that is, the limit of the error in the frame time:

$$E_{LFR} = 0.102 \times 2^{-N} \text{ ms.}$$

By comparing this expression with E_{Lev}, defined previously, where

$$E_{Lev} = 0.83143 \times 2^{-N} \text{ s,}$$

it is clear that both formulas contain the factor 2^{-N}, which may be called an error factor. When N is negative, the value of this error factor becomes larger compared to the value when N is positive. It reaches to a maximum for N = -3 and the minimum for N = 4.

The probable error in the frame time is a variable. Its value really depends on the electronic system and hardware design and is unpredictable.

PROPAGATION TIME AND ERROR

If a spacecraft is placed in an orbit at altitude A, the propagation time, T_p, of a telemetry signal from the spacecraft to the ground network station is

$$T_p = \frac{D}{C},$$

where

D = the distance between the spacecraft and the station, and

C = the speed of light.

The distance D is called the slant range and is a function of time. It must be computed from the spacecraft position vector $\overline{P}$ at time t and the station's position vector $\overline{S}$ in the inertial coordinate system. If $\overline{D}$ is a vector of magnitude D with its direction pointed along the station-to-spacecraft line, the relationship between $\overline{D}$, $\overline{P}$, and $\overline{S}$ is expressed by

$$\overline{D} = \overline{P} - \overline{S}.$$

The inertial coordinate system mentioned here is an earth-centered, right-handed orthogonal system whose Z axis coincides with the North Pole and whose X axis passes through the vernal equinox. Let P_x, P_y, P_z, and S_x, S_y, S_z be the components of P and S, respectively. The calculations of D and T_p are as follows:

$$D = ([P_x - S_x]^2 + [P_y - S_y]^2 + [P_z - S_z]^2)^{1/2}$$

and

$$T_p = \frac{([P_x - S_x]^2 + [P_y - S_y]^2 + [P_z - S_z]^2)^{1/2}}{C}.$$

The position vector $\overline{P}$ (P_x, P_y, P_z) is obtained by orbit determination. Its components are given on the orbit tape at regular time intervals. To obtain $\overline{P}$ at any specified time, interpolation between given position vectors becomes necessary. The position vector $\overline{S}$ of the ground network station is always known, and it is unlikely that a problem would arise in determining the components S_x, S_y, and S_z. However, the determination of vectors $\overline{P}$ and $\overline{S}$ could involve some errors.

While computing the propagation time of telemetry signals, some errors could be introduced into the calculations as discussed below.

- Spacecraft position error—In order to determine the spacecraft position from the orbital information, the correct time must be known. If the time is not known to a millisecond, it is necessary to take into account the amount of possible error or uncertainty in the position vector $\overline{P}$ caused by incorrect time.

  Consideration must also be given to factors such as atmospheric drag, the earth's oblateness, and the effects of the sun and the moon in computing the orbit parameters. It is known that the atmospheric drag fluctuates in a random manner and that the earth oblateness terms dominate for a near orbit. Even though the computer program is complex enough to handle high order perturbation terms, an amount of uncertainty will remain in determining the spacecraft position.

  Obviously, the uncertainty error in the position vector $\overline{P}$ can directly cause the error in the slant range, thereby generating an error in propagation time. If the uncertainty in the position error component along the vector $\overline{D}$ is approximately 33 meters (100 feet), the average error in the propagation time must be approximately 0.1 μs. If the same amount of uncertainty is in the direction perpendicular to the vector $\overline{D}$, then the average error becomes much less than 0.1 μs.

- Ground station position error—Since the slant range is a function of P_x, P_y, and P_z also, it is important that the position of the ground station be accurately established. Currently the positions of ground stations are not accurately known. Typical inaccuracies for most of the ground stations are on the order of approximately 16 meters (≈50 feet), which will introduce an error in the propagation time of about 0.05 μs.

- Factors affecting propagation—In a vacuum, the electromagnetic waves propagate at the velocity of light, which is 299792.5 ± 0.3 km/s. The velocity of propagation changes from this nominal free space value when passing through the earth's atmosphere and ionosphere. For propagation in such mediums as air or the ionosphere, the velocity is measurably slower.

  The index of refraction of the atmosphere is not a constant. It generally ranges from 1.0003 at sea level to 1.00003 at an altitude of about 160 km (100 miles). For a 483-km (300-mile) path, the propagation time error caused by atmospheric refraction is 0.1 μs.

  The ionosphere consists of various layers which are created by the ionization of the upper atmosphere, caused principally by radiation from the sun. The ionosphere presents a discontinuity which affects the propagation of radio waves. The index of refraction of the ionosphere is a variable and is a function of frequency. At frequencies greater than 500 MHz, the path delay caused by the ionospheric refraction is negligible. At lower frequencies, such as 136 MHz, the error of propagation time will be about 0.5 μs. In fact, the characteristics of the various layers change considerably over a diurnal cycle (24 hours), producing corresponding changes in the propagation of waves affected by the ionosphere.

- Equipment delays—The equipment delays usually include the transmission delay from the spacecraft transmitter and the receiving delay from the ground station receiver. These delays can best be measured as functions of temperature, line voltage, or other items ascertained during factory tests before the equipment is installed. No test data are available for reference, and there is no other choice but to make a rough estimate of errors introduced for this reason. The error budget for the propagation time is made up of the above items. The magnitude to be expected is estimated at about 15 μs.

ERROR IN STATION TIME

The ground network stations are equipped with station clocks which are synchronized with UTC time signals. Universal time (UT) is the mean solar time and is based upon the speed of rotation of the earth. The rotation of the earth on its axis is not quite uniform; therefore, UT is not constant. There are three kinds of UT: UT0, UT1, and UT2.*

In order to have a uniform time scale that can be used as a working standard, a UTC is obtained and is maintained by the Bureau International de l'Heure (BIH) in Paris. The rate of UTC is kept constant by reference to cesium beam frequency standards. The U.S. Naval Observatory (USNO) maintains the United States time reference UTC for all United States defense organizations, the Loran-C Stations, and the National Bureau of Standards (NBS) radio stations–WWV, WWVH, and WWVB.

Loran-C is a low-frequency hyperbolic radio navigation system with the capability of worldwide time synchronization. The Loran-C system consists of nine chains with master stations and slave stations.

The transmission of Loran-C stations is synchronized to UTC of the USNO. In general, the time-synchronized Loran-C chain is maintained within ±5 μs of UTC. The pulse signals transmitted by Loran-C stations are at 100 kHz and propagate in two distinct modes–ground waves and sky waves. Ground wave signals can be used for time synchronization of clocks over specific areas of approximately 1600 to 3200 km (1000 to 2000 miles) radius. When the synchronization area is increased to a radius of approximately 6400 km (4000 miles), the use of skywave propagation at night permits the reception of pulse signals at greater distances, but the accuracy obtainable is much less. The functional description of the Loran-C system and its time synchronization are given in the Appendix.†

By using the Loran-C system for clock synchronization (Appendix), the overall error in the network station time comes from the following sources.

- Transmitting system–Error in the transmitting system is caused by instabilities in the master station signals and variations in the time delay between the master transmission and each slave transmission. The error depends on the master transmitter power, noise and interference levels, and the skill and diligence of station operators.
- Propagation prediction–A basic error in this source could start in the computation of the great circle distance between two points whose latitude and longitude are known. Inaccuracies in the precise geographic locations of the transmitter and receiver can produce an error.

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*See *Study of Methods for Synchronizing Remotely-located Clock*, NASA CR-738 Report, Sperry Gyroscope Co., March 1967.

†More details of the Loran-C system are contained in *Study of Methods for Synchronizing Remotely-located Clock*, NASA CR-738 Report, Sperry Gyroscope Co., March 1967.

The ground wave signals are more stable than the sky wave signals; therefore, the ground waves are used mostly for clock synchronization. The propagation time for ground waves is generally affected by three factors: the atmospheric refraction, the earth conductivity, and the vertical lapse rate factor of the permittivity. These factors usually cause the retardation of the ground wave signals and should be taken into account. An artificial correction of these factors is therefore necessary when standard propagation time is calculated. However, an accurate correction is not easy to obtain and an error in propagation prediction can be expected.

The sky waves take several possible hops to reach far distances and require more time to propagate to the receiver. Because the path geometry of sky waves is quite variable, the prediction of propagation time is less accurate. The propagation time for pulse signals generally includes the delay within the receiver which must be measured by a factory test and then added to the computed propagation time. The accuracy to which this delay can be measured depends upon the techniques used and care taken.

- Receiving system—The use of the Loran-C pulse for timing requires the identification of a point of reference of the received pulse and makes a time measurement on that particular point. For ground wave signals, this point of reference can be the third cycle. Therefore, a Loran-C receiving system must make an accurate identification of the proper cycle. If a receiving system fails to identify a particular cycle correctly, an uncertainty in cycle selection will be caused and an error of a multiple of 10 μs in the timing output is introduced.
- Station clock error—The time error, T_{ER}, accumulated by a clock during time t_s, is given in the following expression:

$$T_{ER} = (T_E)_{t_0} + (F_E)_{t_0} \times t_s + 1/2\, A_r t_s^2$$

where

$(T_E)_{t_0}$ = initial time error,

$(F_E)_{t_0}$ = initial frequency error, and

A_r = aging rate, which is the linear frequency drift rate.

If the initial time error and the initial frequency error for a clock are both zero, then

$$T_{ER} = 1/2\, A_r t_s^2.$$

In this case, the clock error is a function of A_r. The aging rate, A_r, for a good standard clock is one part in 10^{10} per day. A cesium beam standard has a drift of less than one microsecond in 10 days. Because cesium beam standards are used in network stations, the clock error is obviously really small and not significant.

The overall error of station time based on the above mentioned sources results in a value which is less than 100 μs. This value is estimated by the timing experts of the Network Engineering Division at GSFC.

ENCODING SYSTEM AND TIMING ERRORS

Time Codes

There are two time codes adopted for use by NASA. They are the 36-bit binary coded decimal (BCD) time code and the serial decimal (SD) time code. These time codes are derived from the same source, the station clock, which is driven by a precision oscillator. The BCD time code consists of time data in digits from seconds through hundreds of days and includes station identification, spacecraft identification, the year of recording, and other parameters. The resolution of BCD time code is one millisecond. The SD time code presents the time data in digits from tens of seconds through tens of hours. It has a resolution of one second, and it possesses less reliability than the BCD time code.

The data from the spacecraft are received by the tracking station through the RF links, and the time codes and the data are recorded simultaneously on the data tape. Because the tape recorder is a basic instrument in the station data acquisition system, timing errors could be caused by such critical factors as flutter, skew, and gap scatter, in addition to the errors introduced by the station clock.

Flutter and Pulse Jitter

Flutter is defined as the deviation in the reproduced frequency from the original, recorded frequency. It is the result of instantaneous tape speed variation caused by various sources, such as irregularities in the surface of the tape or belts and friction between the tape and the heads or guides. During the recording process, the tape transport is required to move the tape across the head at a precisely uniform speed. Any speed variations will have an unwanted modulation of the carrier frequency.

Flutter can be measured by experiment. It is noted that flutter is generally less at a higher tape speed of recording than at lower speeds. If data are recorded at a higher speed but are played back at a lower rate, the effect of flutter is much less than when recording and playback are at the same low speed.

Data can be recorded either by digital or analog techniques, and it is known that analog methods are much more sensitive to flutter than are digital recordings. In analog recording, it is assumed that tape velocity is perfectly constant. During playback, the time scale depends entirely on the mechanical drive to move the tape as it passes the head; therefore, the analog recording techniques are much concerned with flutter. This is quite different from digital recording, where codes are used to represent sampled readings made at equally spaced intervals. As data pulses are recorded at discrete intervals, each reading can be delayed and read out at new and different equal time intervals.

Flutter causes time base distortion and is related to time base error (TBE). The TBE is defined as the total time error measured from a reference point in a single track. It appears as incorrect time base alignment, relative to true absolute time of any single track, and is also called intrachannel time displacement error. It indicates the error in the time between two events recorded on a single track when played back from a tape recording.

The time base error equals the integral of flutter. Its increment is often called pulse jitter, which is the time error incurred over successive sample intervals. The jitter is an indication of momentary movement of playback signal and can be described by mathematical equations.

It is assumed that the data are flutter-free ideal pulses with a frequency of $1/T_a$. The time between consecutive pulses is simply the value of T_a. In this case, T_a is constant and is the sample time interval. If the first pulse occurs at 0 time, the time of the (n+1) pulse starts at

$$T_{[n+1]} = nT_a.$$

If there is now flutter between pulses on playback, the reproduced time intervals, pulse widths, and pulse-to-pulse position will appear incorrect. The time interval T_a therefore represents the average time $T_{[n+1]}/n$ which is assumed to have a limit as n approaches infinity. The time between the *nth* and (n+1) pulse is therefore

$$T_a + \Delta T_n,$$

where ΔT_n denotes the deviation from the average time T_a. The value of ΔT_n is the jitter between successive pulses. The total accumulated jitter of n pulses is then

$$J_n = \sum_{i=1}^{n} \Delta T_i.$$

Therefore, the (n+1) pulse occurs at time

$$T_{n+1} = nT_a + J_n,$$

where the value of J_n can be positive or negative because each ΔT_i possesses either sign. It is possible that there is an integer n such that $J_n = 0$.

Pulse jitter can be measured, and its amount is determined on any tape transport. The measurement of jitter for the tape recorder in the tracking station is usually done by the recorder manufacturer. Unfortunately, no such data are available. The rough estimate of maximum jitter is 0.5 percent of the average time interval T_a. For one millisecond of sample interval, this is about 5 μs.

Skew

Skew is defined as the timing instability between two tracks in a multitrack tape recorder. It is the timing error between tracks irrespective of error in absolute time. Data pulses which make up a given number or character are usually recorded in a parallel fashion simultaneously on different tracks. When the data of multitrack tapes are played back, a true time correlation between the various tracks must be obtained. However, if data signals were recorded on another track at the same time, some signals would be placed on the tape ahead of others. Naturally this skew would cause timing errors in the data signals on playback, because the time relationship between them would be incorrect.

Another type of skew arises because the tape itself is an elastic material and is subject to dimensional change. There is also a tendency for the center line of the tape to depart from a perpendicular to the line of recording when transported across the heads. The deviation of the tape from a linear path would give rise to misalignment of the parallel data in the playback mode. This also would cause relative time error between data signals recorded on different tracks in a multitrack recording. Therefore, skew is also called interchannel time base error (ITBE); it includes both static and dynamic skew.

Static skew refers to the steady components of skew. It is the static time difference between the tracks. This type of error originates from sources such as gap scatter, head stack tilt, or misalignment of the recording and playback heads when separate heads are used. These sources do not vary dynamically during the processing of a given reel of tape on a given tape transport. They are related to the inaccurate mounting of head azimuth or mechanical misalignment of the magnetic head gaps. For instance, if all the center lines of the playback heads are not perpendicular to the direction of the tape movement, a time difference between the data signals immediately follows, even though the signals are recorded simultaneously on different tracks. The static skew can be greatly reduced if magnetic heads are constructed and mounted correctly with precise azimuth alignment such that the gap edges are exactly perpendicular to the tape path. Static skew can be reduced to zero by recording and playing back on the identical tape head on subsequent tape runs.

Dynamic skew refers to the fluctuating components of skew. It is caused by the shearing force across the width of the tape which makes two tracks move with different speeds. The shearing force appears to be the result of nonperpendicular motion of the magnetic tape as it goes over the recording and playback heads. A straight linear shear of the tape from edge to edge would disturb the time correlation between the tracks and could generate differential timing errors in the direction of tape travel. Thus, the dynamic skew is defined as those timing errors originating from the dynamic motion of the tape relative to the heads when the heads are considered as a static positional reference. The dynamic skew is usually shown in the common form of oscillatory weaving, yawing, skewing of the tape in its plane, or the unwanted vibration of the head assembly.

Dynamic skew can be measured as shown in table 2. Because the measurement of dynamic skew for tape recorders used in tracking stations cannot be obtained, the table lists data that are provided by the Bell & Howell Company for a similar tape recorder (VR-3700B magnetic tape recorder/reproducer).

Table 2
Dynamic Skew Within Same Headstack (μs)

Tape Speed (ips)	Track To Adjacent Track 0 to peak	Between Outside Tracks ½-in. Tape 0 to peak	Between Outside Tracks 1-in. Tape 0 to peak
120	0.15	0.40	0.75
60	0.30	0.75	1.5
30	0.60	1.50	3.0
15	1.20	3.00	6.0
7-1/2	2.40	6.00	12.0
3-3/4	4.80	12.00	24.0
1-7/8	9.60	24.00	48.0
15/16	19.20	48.00	96.0

Skew is inversely proportional to tape speed, that is, as tape speed is increased, the timing error is reduced. The selection of a suitable highest tape speed can thus be made such that the timing error reaches a minimum value. Dynamic skew is also directly proportional to the distance between tracks as shown in the above data. Therefore, to decrease the possible skew, timing signals are usually recorded in the track adjacent to the channel that is recording the experimental data.

The tape speed used in instrumentation recorders at tracking stations is generally about 1-7/8 ips; the dynamic skew is estimated to be less than 10 μs.

TIME DECODING SYSTEM AND TIMING ERROR

The time decoding system used at GSFC is a complex system of electronic hardware which provides internal self-checking circuits and computational capabilities. The main functions of this system are to decode the BCD and the SD time codes, to provide millisecond interpolation of time, and to convert the BCD time information into binary words for input to the computer. The mode of operation depends upon the inputs to the system and the internal conditions within the system. The output contains flags to indicate the mode of operation and the results of self-checking and computation.

The input to this decoding system contains the BCD time code or the BCD and SD time codes in the form of a modulated 1-kHz carrier plus a linearizing (or reference) frequency. The station clock oscillator generates the two time codes, and the frequency is divided to provide the linearizing frequency. Therefore, all these inputs are derived from the same single source, the station clock oscillator. The linearizing frequency or the carrier of either time code is used in the time decoding equipment to phase-lock a voltage-controlled oscillator which drives the flywheel. The flywheel produces a nominal 1-kHz signal that is phase-locked to its input, if input exists, and maintains an output at the frequency of the last input if the input is lost. The 1-kHz output of the flywheel updates the accumulator register.

After the time signals are fed to the time decoding equipment, they are filtered and buffered through automatic gain control (AGC) amplifiers. Then the signals are detected and synchronization is acquired. The two time code inputs are sent to two separate time code translators, each of which checks input signals, detects the error, and ensures that the contents in its output provide the best time information to a separate translator register. The two translator registers store the time words and route their outputs to a comparator, where the received time signals are compared to the generated counting accumulator for validity of time information. The comparator also determines which of the two translator registers will be transferred to the accumulator register because of its best estimate of the received time. This accumulator register is incremented by millisecond pulses, and the accumulated time is available as an output to be sent along with the decoded time words to a BCD-to-binary converter. The BCD-to-binary converter unit converts the time word to binary form representing milliseconds of the year or milliseconds of the day and day of the year. A number of status flags are generated which indicate the quality of the received time codes. This status information is used to establish confidence levels in the reliability of the output time. The binary number derived from the time code is therefore updated to obtain the millisecond precision. This converted and updated time word is the time source of experimental data.

The time decoding system possesses built-in redundancy by having both the BCD and SD time codes available for processing. If only one of these two time codes is present, the system will automatically consider only that one. This system performs checks of its internal circuitry automatically, detects the errors in the time signals, and identifies the class of error which has been discovered. The system is also designed to be capable of making automatic tests of its equipment components prior to every function. If any faulty condition is indicated, the output will be flagged and an error light will remain on until the necessary correction is made.

Although this system detects, identifies, and even corrects errors of certain types, the timing error has not been completely eliminated. Undetected errors in the time data still are recorded on the magnetic tape and require computer time to search for them. Most of the time these undetected errors are small and are ignored. Their estimate will be included in the following section.

Since the 1-kHz carrier is a part of the time code, the time decoding system can only decode the time within 1-ms resolution. Therefore, the minimum timing error from the decoding system is estimated as approximately 1 μs.

Other Errors

There are some timing errors which come from sources other than those discussed in the above sections. These errors are very small. For instance, timing delay could occur in the bit synchronizer and digital circuitry during the analog-to-digital conversion process. The delay depends on the equipment selected and its associated circuitry. The magnitude of the timing error caused by such delay is on the order of microseconds. A value of 30 μs is thus estimated for these small errors, including the occasional occurrence of nondetected error in the time decoding system.

TIME CORRELATION

When the spacecraft is commanded by the ground tracking station to do real-time transmission, the time, T_T, at which the data signal is telemetered to earth is approximately the same as the apparent event time, T_{ev}, at which data are sampled (or collected) in order to appear in each minor frame. If the tracking station receives these data at ground time, UTC, the readings of UTC are attached to telemetry data regularly by recording their values in each minor frame. The space data are thus time tagged with ground time. It is then obvious that

$$T_{ev} \approx T_T = \mathrm{UTC} - T_p$$

where T_p is the already known signal propagation time.

The above equation determines the apparent event time, T_{ev}, for experimental data in real-time transmission. It establishes an important relationship between the desired apparent event time and the associated value of ground time. In general, this relationship is then applied to obtain the unknown apparent event time for those data transmitted in playback mode.

Because the data transmitted in playback mode are collected and stored on the spacecraft before the transmission is made, it is true that

$$T_{ev} \neq T_T$$

and

$$T_T = \mathrm{UTC} - T_p.$$

Because most of the data that the tracking station receives are the stored type, the determination of time T_{ev} for any data point of that type is a necessity. If there is a portion of stored data of each orbit appearing also in a real-time transmission mode, then the apparent event time for data of that portion is immediately determined and used. By comparison and extrapolation, the apparent event time for any data in playback mode can be obtained.

TOTAL TIMING ERROR

For convenience, the timing errors examined in this document could be classified into two types: systematic and nonsystematic. The systematic error originates from the hardware design of the spacecraft telemetry system and cannot be decreased. This systematic error is large, but may easily go unnoticed. As indicated earlier, those items which belong to this type include the following:

- Error of spacecraft clock time—As mentioned previously, the spacecraft clock time shown in each major frame represents only one unique value, even though there is a spacecraft clock reading once every 16 minor frames with a total number of 16 times in a major frame. However, all 16 readings are used to repeat one value of clock time, which is not the exact time. The large error contained in that value is called the apparent spacecraft clock time error, E_{sc}, with the magnitude

  $$E_{sc} \leqslant 1.9562986 \text{ s.}$$

- Timing error in observation data—The observational data which appear in each minor frame are also associated with the timing error. From the data obtained, there is no way to determine the exact moment at which each observation is made. It is known that the spacecraft observes each event only within the past m_R seconds if those data are collected only once each minor frame. The timing error involved is called the error of event time, with the estimate

  $$E_{ev} \leqslant m_R = 0.83143 \text{ s}$$

  for the nominal bit rate of 981.4453 bps. Because the spacecraft has the capability of changing its bit rate upon command, the timing error, E_{ev}, estimated for other possible bit rates is

  $$E_{ev} \leqslant 0.83143 \times 2^{-N} \text{ s}$$

  where $N = -3, -2, \ldots .\ 3, 4.$

  The value of E_{ev} also depends on the number of times (ℓ) that same kind of observation with different measurements is sampled per each minor frame. For simplicity, it is assumed that these different results from the same experiment are positioned at equal time intervals, ℓ, in a minor frame. The error, E_{ev}, in this case becomes much less with the amount

  $$E_{ev} \leqslant \frac{0.83143 \times 2^{-N} \text{ s}}{\ell} .$$

  It is planned to use the nominal bit rate most of the time after the spacecraft is launched. The discussion is thus emphasized on the case $N = 0$ and

$$E_{ev} \leqslant \frac{0.83143}{\ell} \text{ s.}$$

It is obvious that E_{ev} decreases as soon as ℓ is increased. However, the integer ℓ for each kind of observation becomes definite once the spacecraft telemetry hardware system is built. This means that E_{ev} cannot be altered freely to reduce the timing error after the electronic instruments for the spacecraft telemetry system are assembled and the necessary circuitry is completed.

- Timing error in frame time–The probable error in the frame time is estimated to be about one-tenth of a bit period. With the nominal bit period of 1.018 ms, the error E_{FR} is estimated with the magnitude

$$|E_{FR}| \leqslant 0.102 \text{ ms.}$$

As the minor frame time will eventually be used instead of the spacecraft clock time, the error in the spacecraft clock time might not be that important in some aspects, but the timing error in the observation data constitutes a major concern. Considering the time accuracy of ±2.6 ms sought by the experimenters, the timing error in the observational data alone is several hundred times that amount.

The second type of timing error is nonsystematic. It is considered as a traditional error which has existed in telemetry data since the first spacecraft was built. It is the error that occurs in the data after the data are sampled (or collected). Those errors discussed previously and belonging to this type are listed below.

Source of Error	Amount of Error (μs)
Propagation time	±15
Station time	±100
Pulse jitter	±5
Skew	±15
Time decoding system	±1000
Other	±30
	RSS* error ≈ 1006 μs

The listed estimates are made to meet the best circumstances, which implies that the equipment is used with minimum timing delays, the correct calculation of spacecraft position with its precise estimate of propagation time, careful skill employed to handle every necessary procedure, and the right technique applied with prudent exercise on required computer programming. Any change in circumstances will result in a larger amount of timing error than the above estimate. For instance, if an operator or a programmer makes a careless

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*RSS = root of the sum of the squares of each item.

mistake, the nonsystematic error could increase to several times the above estimate without its existence being known.

Furthermore, the above estimate is also made under certain prior assumptions. There is no guarantee that these assumptions will always hold true. The occurrence of any one assumption can negate the effect of another. For example, the assumption that the signal-to-noise ratio is high results in a lower estimate for the timing error. What happens if the transmission is suddenly disturbed by a storm? The noise disturbance will give rise to the chance of getting useless data. Data discontinuities might also be created. Therefore, such factors as noise, the data gap, and the time jump become additional sources of timing errors. A special technique is then often needed to identify noise and discard it, to smooth the time and maintain time continuity, and to make time corrections and minimize the timing error.

SUMMARY

A detailed analysis has been made in the study of spacecraft timing errors. The timing errors and the cause of each possible timing inaccuracy have been carefully examined. This study has explored the spacecraft's telemetry system by investigating one specific spacecraft, and the results produced are significant and somewhat general.

It was found that the maximum error of the spacecraft clock time is equal to the value of that clock period. If the clock period value is lowered, the apparent clock timing error is reduced. When the observation data are sampled once per minor frame, the timing errors involved are equal to or less than the minor frame time. If the spacecraft has the capability of varying its bit rate, those errors are inversely proportional to the bit rate. A reduction of timing errors can thus be achieved by decreasing the minor frame time or increasing the bit rate. Further reduction of errors can be accomplished if the number of times for sampling the observation data in each minor frame is increased. All the errors mentioned above belong to the type of systematic errors which are associated directly with the uncertainty of the exact time at which the event occurs. It should be noted that the spacecraft clock period, the minor frame time, the bit rate, the number of times for sampling the data per minor frame, and the bit period are fixed when the spacecraft is built. The reduction of systematic timing errors should be taken into account as early as possible during the design stage of the telemetry system.

Nonsystematic errors were also considered in this study. They are errors entering into the data after they are sampled. This type of timing error is reducible on the ground and is much smaller in comparison to the systematic type. In fact, the nonsystematic errors were the only concern in the past in regard to timing errors. This is because the principal data users are experimenters, and it was believed that the experimenters would have their own means to determine errors in the indicated time of event occurrence as a consequence of spacecraft instrumentation.

In the future, users from universities, private industry, and local and state government will be using the space observation data in addition to those experimenters. Our communities will share the benefits from the development of space technology. For the convenience of users who are not experimenters, it is necessary to emphasize the reduction of systematic-type timing errors as well as the nonsystematic type in order to obtain the required timing accuracy.

The findings presented in this report have applications in future telemetry systems and can provide timing error information for a necessary feedback. It is hoped that this report may serve as a guide to those who need such information and may prevent needless searching.

ACKNOWLEDGMENTS

The author would like to thank Mr. C. M. Stout, Assistant Chief of Information Processing Division; Mr. M. Mahoney, Head of Telemetry Computation Branch; and Mrs. J. M. Stockwell, Head of Project Computation Section, for their assistance and support of this project. The author is also grateful to Mr. R. T. Groves, Chief of Mission Support Computing and Analysis Division; Mr. C. H. Looney, Chief of Mission Operations Computing Division; Mr. Harold Levy, Assistant Head of Data Processing Branch; and Mr. Paul McCeney, Communication Engineer of NASA Headquarters, for their helpful comments and suggestions.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland

SOURCES

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APPENDIX

LORAN-C SYSTEM AND ITS TIME SYNCHRONIZATION

The Loran-C system has been used by the U.S. Coast Guard for navigation purposes on both ships and aircraft for many years. At the present time, this system has nine Loran-C chains located around the world for worldwide time synchronization. Each chain consists of a master transmitting station and three or more slave stations. Both master and slave stations transmit the same identical pulses with the frequency at 100 kHz. Each station transmits a group of eight pulses, in which the separation between the beginning of every pulse and the next one is exactly 1 ms. The master station is identified by the fact that it transmits an additional ninth pulse, which is delayed 2 ms from the eight pulse. The typical Loran-C pulses are shown in figure A-1.

The transmission of the master station comes first and is followed sequentially by the slave stations in a prescribed order: slave A followed by slave B, slave C, and so on. The transmitting sequence (M, A, B, C) is repeated at a rate called group repetition period (GRP) that is unique to each chain. The delay between the master station transmission and each slave transmission is a known constant called the emission delay. The delay is chosen for each slave and must be accurately maintained so that the pulse groups from the stations will not overlap regardless of the reception point. It is the job of slave stations to ensure that their own epochs (first pulse) occur at the prescribed time. The emission delay and the group repetition period are the only differences between the chains in the system.

The transmission of each chain is synchronized to UTC controlled by the U.S. Naval Observatory. The master station monitors the synchronization of each slave within its chain. The accuracy of the synchronization of Loran-C chains is different from one chain to the other. The time error of all synchronized Loran-C chains is contained in USNO daily teletype messages and is also summarized weekly in the USNO bulletin.

A modern Loran-C receiver must have a loop antenna to receive timing signals. Each received signal then enters RF circuitry and passes through a high gain amplifier to increase its amplitude, so that it can be viewed on an oscilloscope. The receiver also contains another circuit with an electronic time interval counter which can be used to compare the Loran-C epoch with the station clock and to measure the time difference between them. The station clock error, E_c, can then be calculated by subtracting the known propagation delay from the measured time difference plus a correction term. That is,

$$E_c = D_t - P_d + E_r$$

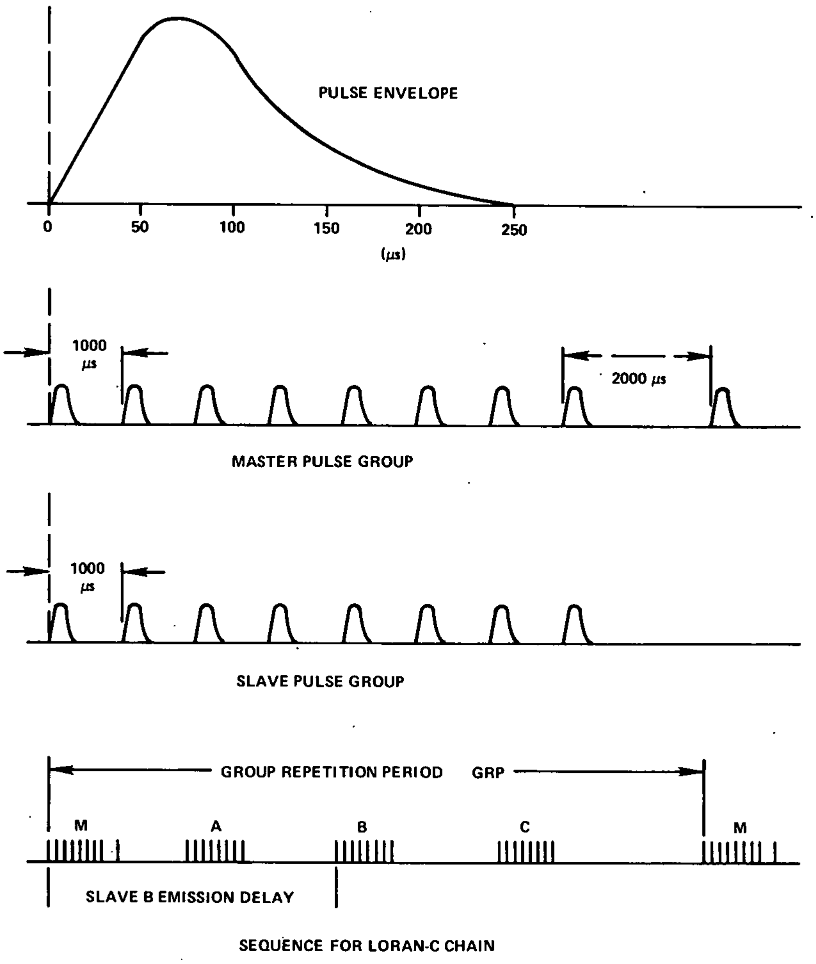

Figure A-1. Typical Loran-C pulses.

where

E_c = the computed error of the ground network station clock from the USNO master clock—E_c is positive if the station clock is slow and negative if the clock is fast.

D_t = the measured time difference between the station clock and the received Loran-C pulse.

P_d = the propagation delay, which is defined as the propagation time from the Loran-C station to the receiver plus the delay within the receiver.

E_r = the correction term for the published error of the Loran-C chain from the USNO bulletin.

If a slave station is used instead of the master's transmission, the emission delay of that particular station must be added to the parameter P_d.

NASA-Langley, 1975

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