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APPLICATION OF SATELLITE TIME TRANSFER IN AUTONOMOUS SPACECRAFT CLOCKS

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ABSTRACT

To meet the needs of spacecraft autonomy, such as a new generation of data collection and handling systems, onboard navigation, etc., an autonomous spacecraft clock (ASC) is being developed. The ASC is designed to provide a standard time scale required by all experimenters in future spacecraft. The ASC is to be synchronized when necessary using such systems as the Tracking and Data Relay Satellite System (TDRSS) or the Global Positioning System (GPS). The TDRSS is a NASA sponsored two-way satellite communication system through which user satellites can receive time signals by a one-way or two-way mode from the ground station. The GPS is a Department of Defense sponsored navigation system through which timing information can be extracted. The conceptual design of an ASC and its synchronization and applications will be discussed.

INTRODUCTION

Since the beginning of history, time has been used to mark the passage of events which in scientific terms is called data. The concept of time and its definition varies with the users. In short, there is not an adequate definition for all users. For the NASA space program, time definitions are found in project documents and in data systems standards.

In early space applications, observations of events were recorded on magnetic tape, [1] stored in a computer memory, and transmitted to the ground in realtime. These data were time tagged by time codes generated onboard the spacecraft. The time code may not necessarily be related to any standard time scale. When realtime data were transmitted from the satellite to a ground station, they were time tagged again by means of the ground station clock (UTC). From the two sets of time tags, the spacecraft clock could be calibrated if the equipment and propagation delay were known. Engineers experienced in information processing tell us that a major difficulty in data processing has been to calibrate and validate the spacecraft clock. In order to appreciate the problem, one has to look in detail at how the spacecraft clock was used in the early days of the space program and to some extent, although improved, is still used today.

Onboard a spacecaft there may be two oscillators; one is used to generate clock pulses in a time counting system, and the other is used to generate data samples and telemetry timing functions, e.g., the time division multiplex bit streams, words, frames, etc. Telemetry frames [2] are divided into two categories: major and minor frames. In a NASA standard spacecraft, a minor frame may contain

1024 bits, but not more than 8192 bits. At the start of each minor frame is a frame synchronization word typically 24 bits in length. The trailing edge of the last bit of this word is the standard reference mark for the onboard clock time code. If the two oscillators are asynchronous, whether because of differential aging rate or off-set frequency between them, one can anticipate time interpolation problems in data reduction. In actual operation, data stored on the spacecraft may be transmitted to the ground in reverse order because the spacecraft magnetic tape is played back in the reverse direction. These data may be time tagged with a time code generated by the ground station clock and recorded again on a magnetic tape as they are received in a ground station. The ground station clock is synchronized to a national standard clock such as the National Bureau of Standards via WWV or the United States Naval Observatory via LORAN C. The data recorded at the ground tracking station are sent by mail or communication links to the data processing facilities at Goddard.

The data reduction problem becomes obvious when one tries to calibrate the satellite clock. [3] This is because to calibrate the satellite clock requires the transmission of the clock word to the ground station in realtime and the removal of the equipment delay and the propagation path delay. The propagation path delay can be removed only after the refined orbital data becomes available. This delay is between 2 to 4 weeks at present. Thus, correlation and corrections of the time codes and data samples generated by the two oscillators onboard the spacecraft and with the time codes generated by the ground station clock are often a major task of data reduction. In retrospect, many of these problems could have been avoided by a well designed satellite clock system. Like many other problems in space programs, the priority has been given to the major thrust of space exploration. This means successful launches of spacecrafts in orbit. Not until the early 1970's did we develop new concepts in autonomous modes of operation of spacecraft clock, navigation, and data handling, management, and transmission. This paper deals with the clock portion of the autonomous spacecraft.

APPLICATION OF AUTONOMOUS SPACECRAFT CLOCK TO NASA SPACECRAFT.

The term autonomous spacecraft clock implies that the clock is synchronized to a time scale without the need for additional calibration and validation. The time code distribution to the users is handled through onboard computers, without human intervention for extended periods. The conceptual block diagram of such a clock is shown in Figure 1. In this figure, it is assumed that a clock calibration message is received onboard the spacecraft in realtime with all propagation delays removed to a level of error lower than the accuracy of time-keeping required by the users. There is a time interval unit with which the onboard clock error can be measured relative to the received time signal. This clock error is stored in the memory unit and compared with a pre-determined tolerable error. If the measured clock error exceeds the tolerable error, the onboard clock is corrected automatically unless the correction operation is overridden by a ground command. The clock error can be transmitted to the ground for verification. In addition, the received time signal can be transmitted back to the ground for propagation delay measurement using the two-way time transfer technique. As one can see from this figure, a parallel grouped-binary time code (PB5) is generated and distributed to users and is incorporated in telemetry data packets. Additionally, time pulses and frequency signals are provided from the clock to the experimenters for sensor control and/or phase lock of other onboard oscillators and to the telemetry system. The central theme of this approach is to provide a coherent signal in frequency and time onboard the spacecraft and to provide a time scale that can be related to any national time standard.

PHILOSOPHY OF OPERATION

The design of the NASA autonomous spacecraft clock follows the philosophy that the performance of the clock meets the users requirements for time by a safety factor such that the clock need not be corrected more than once a week. While the clock can be checked as often as a space project requires, it is considered that once per day should be sufficient. Obviously, the reliability of the clock for continuous operation for at least three years must be built into the system.

Clock corrections are made in steps of frequency or time (depending on the type of oscillator) smaller than the resolution requirements of the users. Table 1 shows the clock errors accummulated over the periods shown for typical performance of the frequency standard oscillators. For most of the known users, timing requirements are shown in Table 2. The majority of applications still have accuracy requirements in the region of tens of hundreds of microseconds (us) and above with only a few in the order of microseconds and below. Assuming 10 us is the timing accuracy requirement, an oscillator with a timing stability of 1×10^{-11} is sufficient to maintain a clock with a systematic error of less than 10 us per week. Such a stability requirement can be met by a quartz crystal controlled oscillator. The clock error may be corrected by a step-frequency correction as shown in Figure 2. If an atomic oscillator such as a rubidium gas cell or cesium beam tube type is used, the correction may be achieved through a step-time correction as shown in Figure 3. It is obvious that the correction mode is arbitrary. Primary consideration is given, however, to simple and periodic field operations by untrained personnel. Thus, if the clock error is due to systematic frequency drift, step-frequency corrections is preferred. On the other hand, if the clock error is due to an off-set frequency resulting from random frequency walk, the correction is made by step-time.

TIME CODE

The time code under consideration for use onboard a spacecraft is a grouped parallel binary time code. [4] This time code as shown in Figure 4 has five groups. The first group, TJD, is a four digit day count truncated from

Julian Day Number (JDN), thus the name Truncated Julian Day, and has a long repetition period of 27.379 years. It is an easy day count system to generate and gives the coarse time information without any need to account for the leap year day. Its relationship to the JDN is shown in Table 3. The next group (Figure 4) is the seconds of a day. After this are three more groups as shown: milliseconds of a second, microseconds of a millisceond, and nanoseconds of a microsecond. As can be easily seen, each group in this time code can be truncated. This is done from the least significant group upward to the resolution of time required without affecting the integrity of the time code. In the time code format shown, four resolution options are offered: second, millisecond, microsecond and nanosecond resolutions. Further, a variable prefix code of 1 to 3 bits is used to identify the four options. Each option of the time code is formatted into an integer number of 8 bit bytes. Thus the code lengths of the four options are 4, 6, 7, and 8 bytes words. The design of this code is nearly maximum in its efficiency of using binary bits; only millisecond and microsecond resolution codes require 4 and 2 filler bits respectively.

The time code is under consideration for use in the data packetization of the NASA End-to-End Data System (NEEDS). Each data packet is time tagged onboard the spacecraft before transmission to the ground. A typical data packet format[5] is shown in Figure 5. The time code is in the secondary header.

OTHER APPLICATIONS

The autonomous spacecraft clock can be used to provide a clock time for navigation when the timing information is not provided by the navigation system. It can be used to control the sensor in a spacecraft as mentioned earlier and can be used to compare another time signal such as that from GPS. If the cost is not a serious consideration, it can be used on the ground in remote sites for timekeeping and control, and to check another time transfer system with equal capabilities and accuracies.

CONCLUSION

The implementation of the concept of an autonomous clock or spacecraft clock has been long over due. The autonomously operated clocks not only achieve simplier procedures and shorter lead times for data processing, but also contribute to spacecraft autonomy for onboard navigation and data packetization. It is anticipated that the hardware design of the autonomous spacecraft clock system will be completed by 1980 and an operational clock system will become available in the 1981 to 1982 time frame.

ACKNOWLEDGEMENT

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REFERENCES

1. Magnetic Tape Track Standard, pp III-4.4 and 4.6, Section 4, Part III, Associated Systems Standards of Aerospace Data Systems Standards (March 10, 1966) GSFC document X-560-63-2, July 1, 1971.

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3. Spacecraft Clock Systems Standard, pp III-2.3, Section 2, Part III, Associated Systems Standards of Aerospace Data Systems Standards (April 23, 1964), GSFC Document X-560-63-2, July 1, 1971.

4. Parallel Binary Time Code for Packet Data and Other Space and Ground Applications - PB5, Part 5, Clock and Time Code Standard of Aerospace Data Systems Guideline, September 12, 1979 (Preliminary).

5. Space Data Packetization Guideline, Part 3, Telemetry Standards, Aerospace Data Systems Standard, August 21, 1979 (Preliminary)

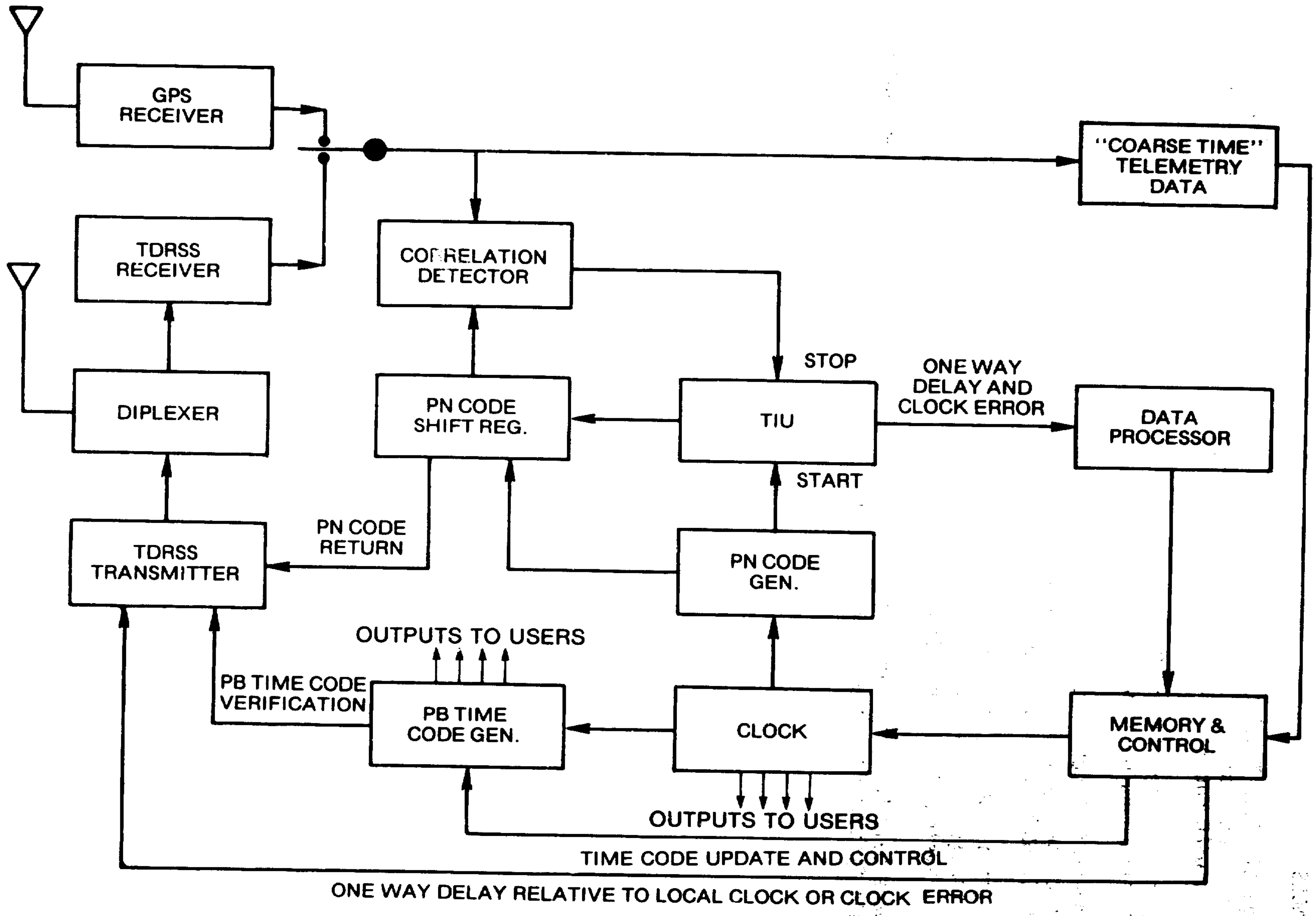
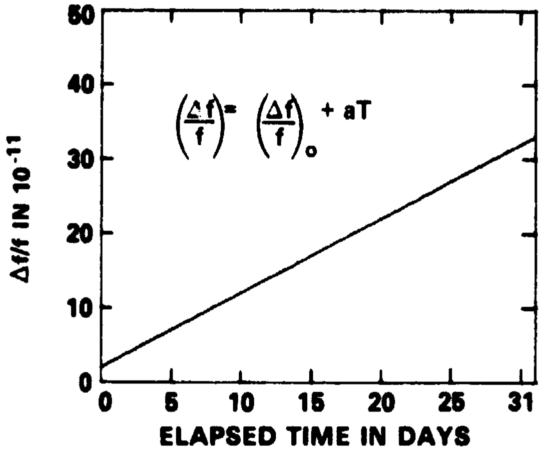
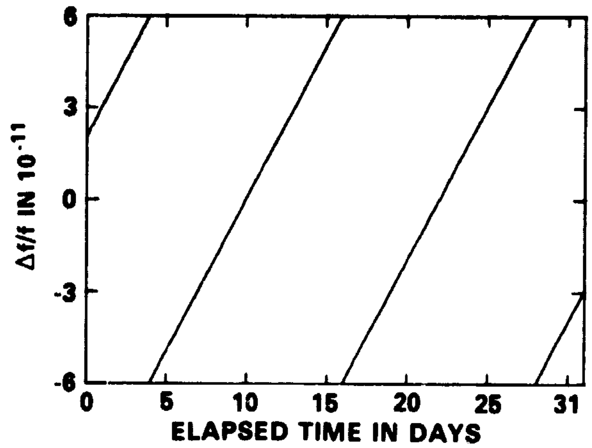


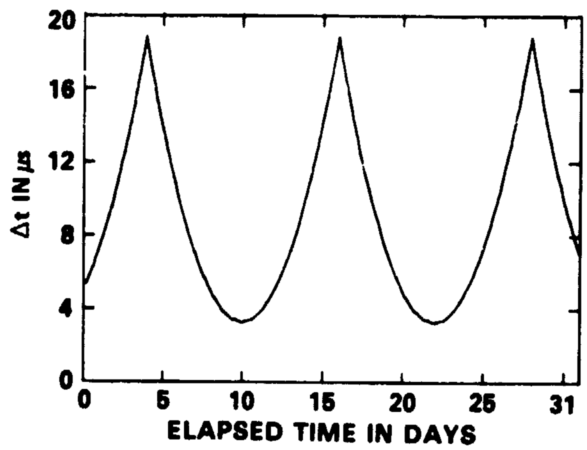
Figure 1. Conceptual Functional Block Diagram of Satellite Clock System



A. FREQUENCY DRIFT OF A TYPICAL QUARTZ CRYSTAL OSCILLATOR AS A FUNCTION OF TIME

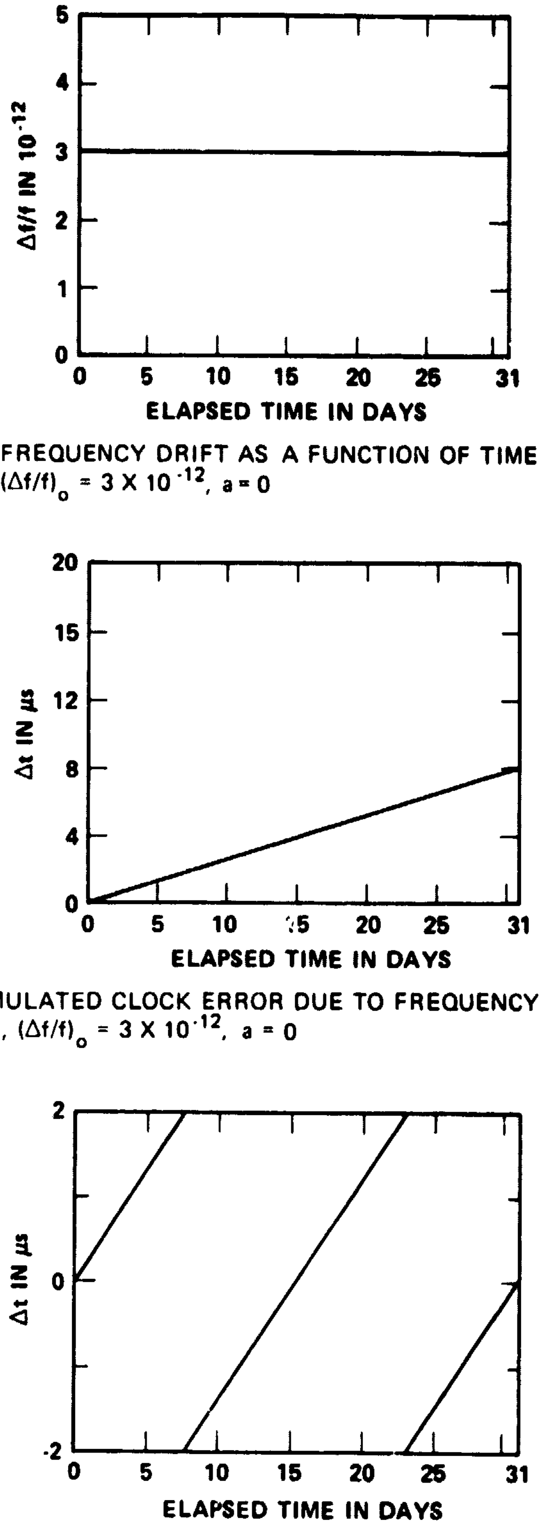


B. RESIDUAL FREQUENCY ERRORS AFTER STEP-FREQUENCY CORRECTIONS; $(\Delta f/f)_o = 2 \times 10^{-11}$ AND $a = 1 \times 10^{-11}$ PER DAY



C. RESIDUAL CLOCK ERRORS AFTER STEP-FREQUENCY CORRECTIONS; $\Delta t_o = 5\mu s$

Figure 2. Clock Keeping by Step–Frequency Corrections

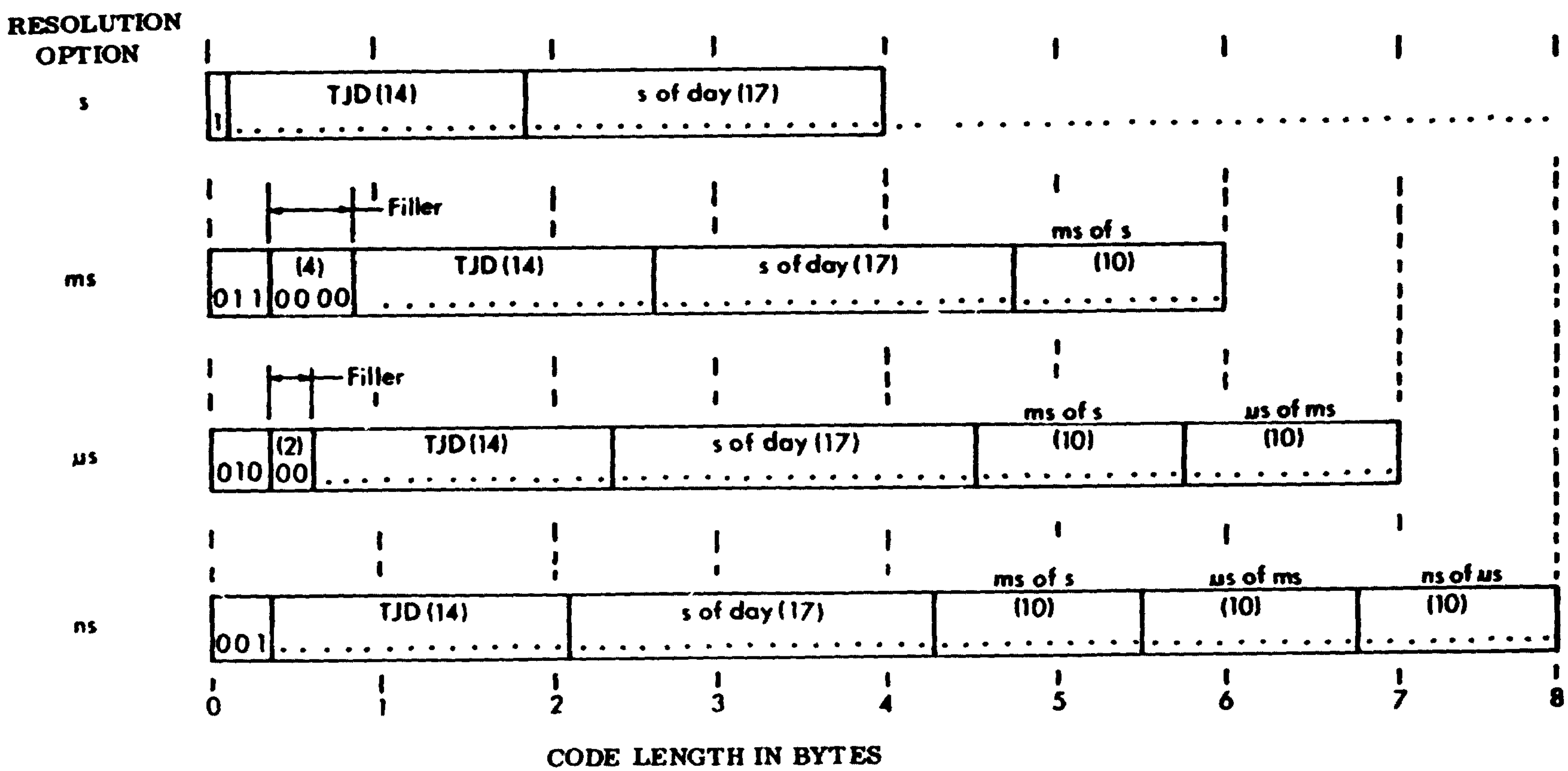


FREQUENCY DRIFT AS A FUNCTION OF TIME
$(\Delta f/f)_o = 3 \times 10^{-12}$, $a = 0$

ACCUMULATED CLOCK ERROR DUE TO FREQUENCY OFF-SET
$\Delta t_o = 0$, $(\Delta f/f)_o = 3 \times 10^{-12}$, $a = 0$

RESIDUAL CLOCK ERRORS AFTER STEP-TIME CORRECTIONS
$\Delta t_o = 0$, $(\Delta f/f)_o = 3 \times 10^{-12}$, $a = 0$

Figure 3. Clock Keeping by Step–Time Corrections



NOTE:

THE DOTS REPRESENT BITS.

THE NUMBERS IN PARENTHESES REPRESENT THE NUMBER OF BITS IN EACH GROUP.

Figure 4. Resolution Options and Identifications of Parallel Grouped Binary Time Code, PB–5

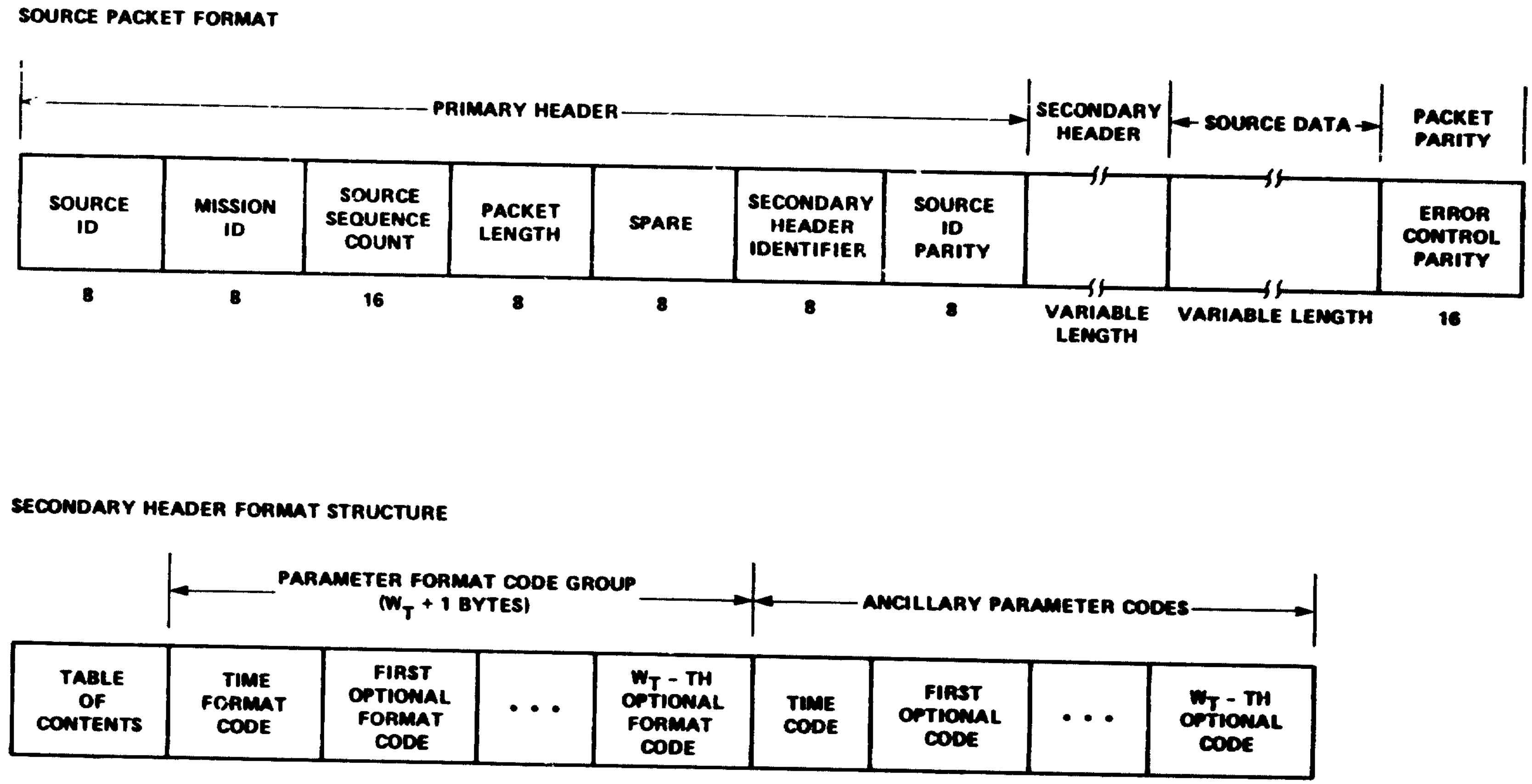


Figure 5. Packet Telemetry Format