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NAVSTAR GPS L5 Signal Specification

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Prepared by SC-159

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FOREWORD

This report was prepared by Special Committee 159 (SC-159) and approved by the RTCA Program Management Committee (PMC) on December 14, 2000.

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- developing consensus on the application of pertinent technology to fulfill user and provider requirements, including development of minimum operational performance standards for electronic systems and equipment that support aviation; and

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1 Introduction

1.1 Scope

This Signal Specification defines the requirements related to the signal interface between the Space Segment (SS) of the Global Positioning System (GPS) and the GPS Navigation Users for the L5 Navigation Signal.

1.2 Signal Specification Approval and Changes

RTCA is responsible for the basic preparation, approval, distribution, and retention of the Signal Specification.

Notes:

1. *The U.S. Department of Defense (DoD) will generate a GPS Interface Control Document (ICD) based on this document (after approval of this document by the U.S. Interagency GPS Executive Board). To facilitate conversion to an ICD, this document follows the section numbering convention and section titles used by previous DoD GPS ICDs.*

2. *The L5 signal design, as documented in this document, is complete. However, specific values for various low-level requirements remain to be specified based upon space vehicle (SV) design tradeoffs that will be conducted by the Block IIF contractor under the constraints imposed by high-level performance requirements. Notes are included in sections of this document that include a low-level requirement with a value to-be-determined.*

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2 Applicable Documents

2.1 Government Documents

Department of Defense (2000). *NAVSTAR GPS Space Segment/Navigation User Interfaces*, Interface Control Document (ICD-GPS-200C), Department of Defense, Washington, DC.

2.2 Non-Government Documents

None.

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3 Requirements

3.1 Signal Definition

The signal interface between the GPS Space Segment (SS) and the GPS Navigation Users consists of three radio frequency (RF) links: L1, L2 and L5. Utilizing these links, the space vehicles (SVs) of the SS will provide continuous earth coverage for signals that provide to the users the ranging codes and the system data needed to accomplish GPS navigation. These signals will be available to a suitably equipped user with RF visibility to an SV. The L1 and L2 RF links are specified in ICD-GPS-200C. Only the L5 link and its relationship with the L1 and L2 links will be specified herein.

3.2 Signal Identification

The carriers of the L5 signal are modulated by two bit trains in phase quadrature. One is a composite bit train generated by the Modulo-2 addition of a pseudo-random noise (PRN) ranging code, synchronization sequence and the downlink system data (referred to as NAV data), and the other is modulated only with a PRN ranging code and synchronization sequence that differ from the ranging code used with the NAV data.

3.2.1 Ranging Codes

Two pseudo random noise (PRN) ranging codes are transmitted on L5: the in-phase code (denoted as the I5-code), and the quadraphase code (denoted as the Q5-code). Code-division-multiple-access techniques allow differentiating between the SVs even though they all transmit at the same L5 frequency. The SVs will transmit intentionally "incorrect" versions of the I5 and the Q5 codes when needed to protect the users from receiving and utilizing anomalous NAV signals resulting from a malfunction in the SV. These two "incorrect" codes are termed non-standard I5 (I5NS) and non-standard Q5 (Q5NS) codes.

3.2.1.1 L5-Codes

The PRN L5-codes for SV ID number i are independent, but time synchronized, ranging codes, $I5_i(t)$ and $Q5_i(t)$, of 1 millisecond in length at a chipping rate of 10.23 Mbps. For each code, the 1-millisecond sequences are the Modulo-2 sum of two sub-sequences referred to as XA and XB_i; their lengths are 8,190 chips and 8,191 chips, respectively, that restart to generate the 10,230-chip code. The XB_i sequence is selectively delayed, thereby allowing the basic code generation technique to produce a set of 74 (37 I5 and 37 Q5) mutually exclusive code sequences of 1-millisecond in length. Of these, 32 pairs are designated for use by SVs, while the remaining 5 pairs are reserved. Assignment of these code phase segments by SV-ID number (or other use) is given in Table 3-I. SV-ID numbers and PRN are identical to those for the L1 and L2 signals as specified in ICD-GPS-200C.

The 74 codes are a selected subset of over 4000 possible codes that could be generated using the selective delay. The remaining codes are reserved for other L5 signal applications such as Satellite Based Augmentation System (SBAS) satellite signals.

Table 3-I. Code Phase Assignments (sheet 1 of 2)

GPS PRN Signal No.*	XB Code Advance – Chips**		Initial XB Code State***	
	I5	Q5	I5	Q5
1	266	1701	0101011100100	1001011001100
2	365	323	1100000110101	0100011110110
3	804	5292	0100000001000	1111000100011
4	1138	2020	1011000100110	0011101101010
5	1509	5429	1110111010111	0011110110010
6	1559	7136	0110011111010	0101010101001
7	1756	1041	1010010011111	1111110000001
8	2084	5947	1011110100100	0110101101000
9	2170	4315	1111100101011	1011101000011
10	2303	148	0111111011110	0010010000110
11	2527	535	0000100111010	0001000000101
12	2687	1939	1110011111001	0101011000101
13	2930	5206	0001110011100	0100110100101
14	3471	5910	0100000100111	1010000111111
15	3940	3595	0110101011010	1011110001111
16	4132	5135	0001111001001	1101001011111
17	4332	6082	0100110001111	1110011001000
18	4924	6990	1111000011110	1011011100100
19	5343	3546	1100100011111	0011001011011

* PRN sequences 33 through 37 are reserved for other uses (e.g. ground transmitters).

** XB Code Advance is the number of XB clock cycles beyond an initial state of all 1s.

*** In the binary notation for the first 13 chips of the I5 and Q5 XB codes as shown in these columns. The rightmost bit is the first bit out. Since the initial state of the XA Code is all 1s, these first 13 chips are also the inverse of the initial states of the I5 or Q5 Codes.

Note: The code phase assignments constitute inseparable pairs, each consisting of a specific I5 and a specific Q5 code phase, as shown above.

Table 3-I. Code Phase Assignments (sheet 2 of 2)

GPS PRN Signal No.*	XB Code Advance – Chips**		Initial XB Code State***	
	I5	Q5	I5	Q5
20	5443	1523	0110101101101	1100001110001
21	5641	4548	0010000001000	0110110010000
22	5816	4484	1110111101111	0010110001110
23	5898	1893	1000011111110	1000101111101
24	5918	3961	1100010110100	0110111110011
25	5955	7106	1101001101101	0100010011011
26	6243	5299	1010110010110	0101010111100
27	6345	4660	0101011011110	1000011111010
28	6477	276	0111101010110	1111101000010
29	6518	4389	0101111100001	0101000100100
30	6875	3783	1000010110111	1000001111001
31	7168	1591	0001010011110	0101111100101
32	7187	6518	0000010111001	0101111100001
33	7329	749	1101010000001	1011001000100
34	7577	1138	1101111111001	1011000100110
35	7720	1661	1111011011100	0110010110011
36	7777	3210	1001011001000	0011110101111
37	8057	4332	0011010010000	0100110001111

* PRN sequences 33 through 37 are reserved for other uses (e.g. ground transmitters).

** XB Code Advance is the number of XB clock cycles beyond an initial state of all 1s.

*** In the binary notation for the first 13 chips of the I5 and Q5 XB codes as shown in these columns. The rightmost bit is the first bit out. Since the initial state of the XA Code is all 1s, these first 13 chips are also the inverse of the initial states of the I5 or Q5 Codes.

Note: *The code phase assignments constitute inseparable pairs, each consisting of a specific I5 and a specific Q5 code phase, as shown above.*

3.2.1.2 Non-standard Codes

The I5NS and Q5NS codes, used to protect the user from a malfunction in the SV (reference paragraph 3.2.1), are not for utilization by the user and, therefore, are not defined in this document.

3.2.2 NAV Data

The system data, D(t), includes SV ephemerides, system time, SV clock behavior data, status messages and time information, etc. The 50 bps data is coded in a rate ½ convolutional coder. The resulting 100 sps symbol stream is Modulo-2 added to the I5 code only; the resultant bit-trains are used to modulate the L5 in-phase (I) carrier. The content and characteristics of data ID number 2 (TBR) are given in Appendix I of this document. In general, the data content is based on that modulated on the C/A and P(Y) codes in the L1 and L2 channels of the SV, with data specific to the L5 signal added. However, the data format is not identical to that modulated on the L1 and L2 channels. Furthermore, a different error detection encoding (CRC) is used.

The L5 quadraphase (Q) carrier has no data.

3.2.3 L5 Signal Structure

The L5 link consists of two carrier components that are in phase quadrature with each other. Each carrier component is bi-phase shift key (BPSK) modulated by a separate bit train. One bit train is the Modulo-2 sum of the I5 code, NAV data, and synchronization sequence while the other is the Q5 code with no data, but with another synchronization sequence. For a particular SV, all transmitted signal elements (carriers, codes, synchronization sequences and data) are coherently derived from the same on-board frequency source.

3.3 Signal Characteristics

The characteristics specified in the following define the requisite characteristics of the L5 signals.

3.3.1 Composite Signal

The following criteria define the characteristics of the composite L5 signal.

3.3.1.1 Frequency Plan

The L5 signal is contained within a 24 MHz band centered about L5. The carrier frequencies for the L1, L2 and L5 signals are coherently derived from a common frequency source within the SV. The nominal frequency of this source – as it appears to an observer on the ground – is 10.23 MHz. The SV carrier frequency and clock rates – as they would appear to an observer located in the SV – are offset to compensate for relativistic effects. The clock rates are offset by $\Delta f/f = -4.4647E-10$, equivalent to a change in the I5 and Q5-code chipping rate of 10.23 MHz offset by a $\Delta f = -4.5674E-3$ Hz. This is equal to 10.22999999543 MHz. The nominal carrier frequency (f_0) – as it appears to an observer on the ground – is 1176.45 MHz, or 115 times 10.23 MHz.

3.3.1.2 Correlation Loss

Correlation loss is defined as the difference between the SV power received in a 20.46 MHz bandwidth and the signal power recovered in an ideal correlation receiver of the same bandwidth.

Note: *This paragraph will be updated based upon SV design. A section will be added to Section 6 that will describe the signals bandwidth characteristics to allow the users to determine their own correlation loss.*

3.3.1.3 Carrier Phase Noise

Note: *This paragraph will specify the phase noise spectral density of the unmodulated carrier and will be based upon SV design. The actual phase noise characteristics will be placed in Section 4.*

3.3.1.4 Spurious Transmissions

In-band spurious transmissions will be at least 40 dB below the unmodulated L5 carrier over the allocated 24 MHz channel bandwidth.

3.3.1.5 Phase Quadrature

The two L5 carrier components modulated by the two separate bit trains (I5-code plus data and Q5-code with no data) will be in phase quadrature (within ±100 milliradians) with the Q5 signal carrier lagging the I5 signal by 90 degrees. Referring to the phase of the I5 carrier when $I5_i(t)$ equals zero as the "zero phase angle", the I5- and Q5-code generator output controls the respective signal phases in the following manner: when $I5_i(t)$ equals one, a 180-degree phase reversal of the I5-carrier occurs; when $Q5_i(t)$ equals one, the Q5 carrier advances 90 degrees; when the $Q5_i(t)$ equals zero, the Q5 carrier is retarded 90 degrees (such that when $Q5_i(t)$ changes state, a 180-degree phase reversal of the Q5 carrier occurs). The resultant nominal composite transmitted signal phases as a function of the binary state of the modulating signals are as shown in Table 3-II.

3.3.1.6 User-received Signal Levels

The SV will provide L5 navigation in accordance with the minimum levels specified in Table 3-III into a 3 dB_i linearly polarized user receiving antenna (located near ground) at worst normal orientation, when the SV is above a 5-degree elevation angle. Additional related data is provided as supporting material in paragraph 4.3.1.

Note: *This paragraph will be updated based upon SV design. A section will be added to Section 6 that will describe the signals bandwidth characteristics to allow the users to determine their own correlation loss. It will specify transmitted power and the supporting material will include typical link budget computations and an SV antenna pattern.*

Table 3-II. Composite L5 Transmitted Signal Phase		
Nominal Composite L5 Signal Phase*	Code State	
	I5	Q5
0°	0	0
-90°	1	0
+90°	0	1
180°	1	1
* Relative to 0, 0 code state with positive angles leading and negative angles lagging.		

Table 3-III. Received Minimum L5 RF Signal Strength		
Channel	Signal	
	I5	Q5
L5	-157 dBW	-157 dBW

3.3.1.7 Equipment Group Delay

Equipment group delay is defined as the delay between the L-band radiated output of each individual ranging signal from a specific SV (measured at the antenna phase center) and the output of that SV's on-board frequency source; the delay consists of a bias term and an uncertainty. The bias terms for L1 C/A and L5-Q5 is of no concern to the users of the L1-C/A and L5-Q5 codes since it is included in the clock correction parameters relayed in the NAV data, and is therefore accounted for by the user computations of system time (reference paragraph 10.3.3.1.3.1). However, single frequency L1-C/A, L2-C/A, and L5 users must correct for the delay between the composite L1/L5 time and these single frequency codes. The uncertainty (variation) of these delays is defined in the following. The relationship of the timing between composite L1/L2 P(Y)-code timing ("P(Y) GPS Time") and composite L1-C/A and L5-Q codes ("L5 Time") is also defined.

3.3.1.7.1 Group Delay Uncertainty

Note: *This section will specify the effective uncertainty of the group delay in terms of a maximum two-sigma value for time constants of interest. This update will occur based upon SV design.*

3.3.1.7.2 Group Delay Differential

The group delay differential between the radiated composite L1-C/A code and L5-Q5 code and single frequency L1-C/A, L2-C/A, L5-I5 and L5-Q5 codes are specified as consisting of random plus bias components. The mean differential is defined as the bias component and will be either positive or negative. For a given navigation payload redundancy configuration, the absolute value of the mean differential delay will not exceed 30.0 nanoseconds. The group delay difference between the L5-Q5 signal and that represented in the SV L5 clock corrections will be broadcast in the L5 NAV message.

Note: *This section will be updated, based upon SV design, to include a specification on the random variations about the mean in terms of a maximum two-sigma value for time constants of interest.*

3.3.1.7.3 GPS Differential Timing

The group delay differential between the radiated composite L1/L2 P/Y code signal and the composite L1-C/A and L5-Q5 signal is specified as consisting of random plus bias components. The mean differential is defined as the bias component and will be either positive or negative. The group delay difference between the P(Y) and L5 GPS timing will be broadcast in the L5 NAV message.

Note: *This section will be updated, based upon SV design, to include a specification on the absolute value of the mean (not-to-exceed) for a given navigation payload redundancy configuration and random variations about the mean (in terms of a maximum two-sigma value for time constants of interest).*

3.3.1.8 Signal Coherence

All transmitted signals for a particular SV will be coherently derived from the same on-board frequency standard; all digital signals will be clocked in coincidence with the PRN transitions for the P-code signal and occur at the P-code signal transition speed.

Note: *This section will be updated, based upon SV design, to include a specification for the average time difference (two-sigma) between the data transitions of the two modulating signals (i.e., that containing the I5-code and that containing the Q5-code) on the L5 channel.*

3.3.1.9 Signal Polarization

The transmitted signal will be right-hand circularly polarized (RHCP).

Note: *This section will be updated, based upon SV design, to include a specification for the L5 ellipticity (maximum, in dB) for the angular range of ±14.3 degrees from boresight.*

3.3.2 PRN Code Characteristics

The characteristics of the I5- and the Q5-codes are defined below in terms of their structure and the basic method used for generating them. Figures 3-1 and 3-2 depict simplified block diagrams of the scheme for generating the 10.23 Mbps

$I5_i(t)$ and $Q5_i(t)$ patterns, and for Modulo-2 summing the I5 patterns with the NAV bit train, D(t), which is rate 1/2 encoded and clocked at 100 sps. In addition, the 100 sps symbols are modulated with a 10-bit Neuman-Hoffman code that is clocked at 1 kHz. The resultant composite bit trains are then used to modulate the L5 in-phase carrier. The Q5-code is modulated with a 20-bit Neuman-Hoffman code that is also clocked at 1 kHz.

3.3.2.1 Code Structure

The $I5_i(t)$ pattern (I5-code) and the $Q5_i(t)$ pattern (Q5-code) are both generated by the Modulo-2 summation of two PRN codes, XA(t) and $XBI_i(n_{Ii}, t)$ or $XBQ_i(n_{Qi}, t)$, where n_{Ii} and n_{Qi} are initial states of XBI_i and XBQ_i for satellite i. There are over 4000 unique XB codes generated using different initial states of which 74 are assigned and identified in Table 3-I using the same basic code generator.

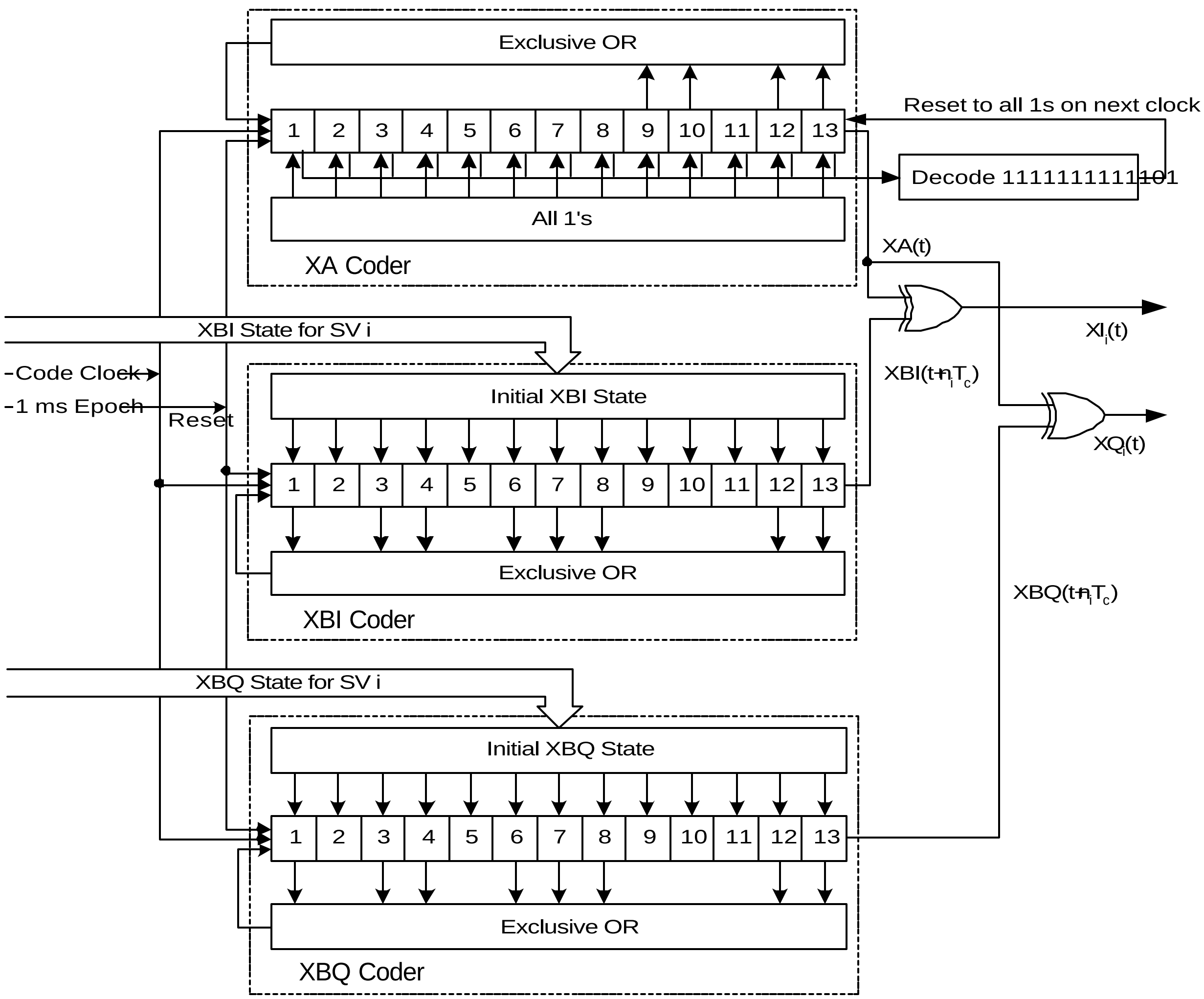


Figure 3-1. Generation of Codes

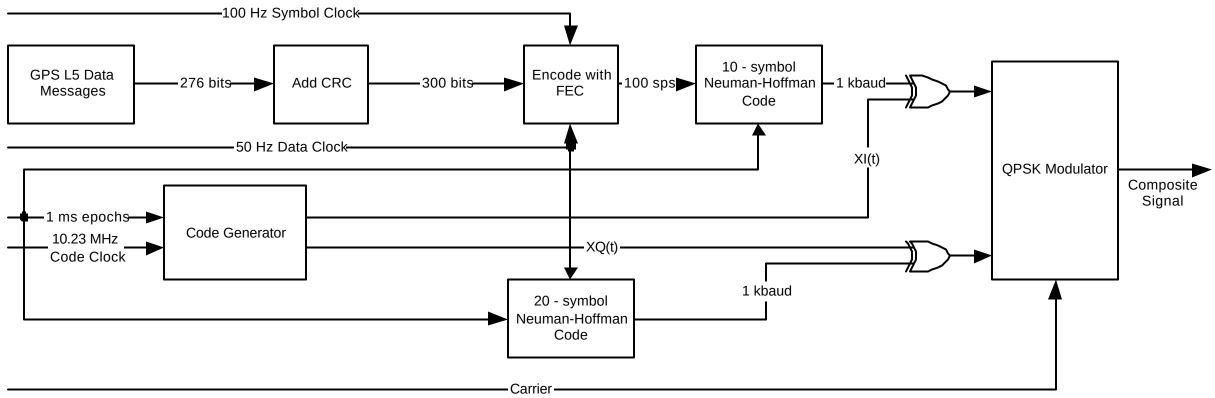


Figure 3-2. Modulation of Signals

3.3.2.2 Code Generation

Each $I5_i(t)$ pattern (I5-code) and $Q5_i(t)$ pattern (Q5-code) are the Modulo-2 sum of two extended patterns clocked at 10.23 Mbps (XA and XBI_i or XBQ_i). XA is an 8190-length code, with an initial condition of all 1s, that is "short-cycled" 1-chip before its natural conclusion and restarted to run over a period of 1 millisecond (synchronized with the L1 frequency C/A code) for a total of 10,230 chips. The XBI_i and XBQ_i, with initial conditions indicated in Table 3-I, are 8191-length codes that are not "short-cycled". They are restarted at their natural completion and run over a period of 1 millisecond (synchronized with the XA code) for a total of 10,230 chips. The polynomials for XA and XBI_i or XBQ_i codes, as referenced to the shift register input, are:

XA: $1 + x^9 + x^{10} + x^{12} + x^{13}$, and
XBI_i or XBQ_i: $1 + x + x^3 + x^4 + x^6 + x^7 + x^8 + x^{12} + x^{13}$.

Samples of the relationship between shift register taps and the exponents of the corresponding polynomial, referenced to the shift register input, are as shown in Figures 3-3 (XA code) and 3-4 (XB codes). In the case of the XB codes, the shift register can either be initialized with all 1s and delayed n_i states as specified in Table 3-I, or initialized with the state indicated in Table 3-I.

The state of each generator can be expressed as a code vector word which specifies the binary sequence constant of each register as follows: (a) the vector consists of the binary state of each stage of the register, (b) the stage 13 value appears at the right followed by the values of the remaining states in order of descending stage numbers, and (c) the shift direction is from lower to higher stage number with stage 13 providing the current output. This code vector convention represents the present output and 13 future outputs in sequence. Using this convention, at each XA epoch (state 8190), the XA shift register is initialized to the code vector 1111111111111, while at each XB epoch (state 8191), the XB shift register is initialized to a code vector peculiar to the PRN number and phase. The XB code vectors are as indicated in Table 3-I. Alternatively, the XB shift register is initialized to the code vector 1111111111111 and advanced n_i states as indicated in Table 3-I.

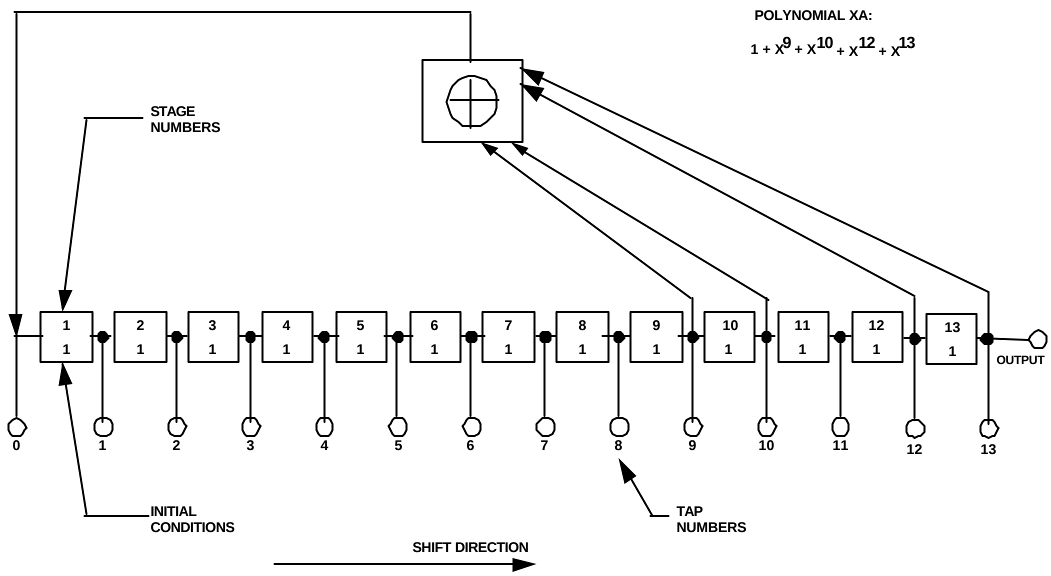


Figure 3-3. XA Shift Register Generator Configuration

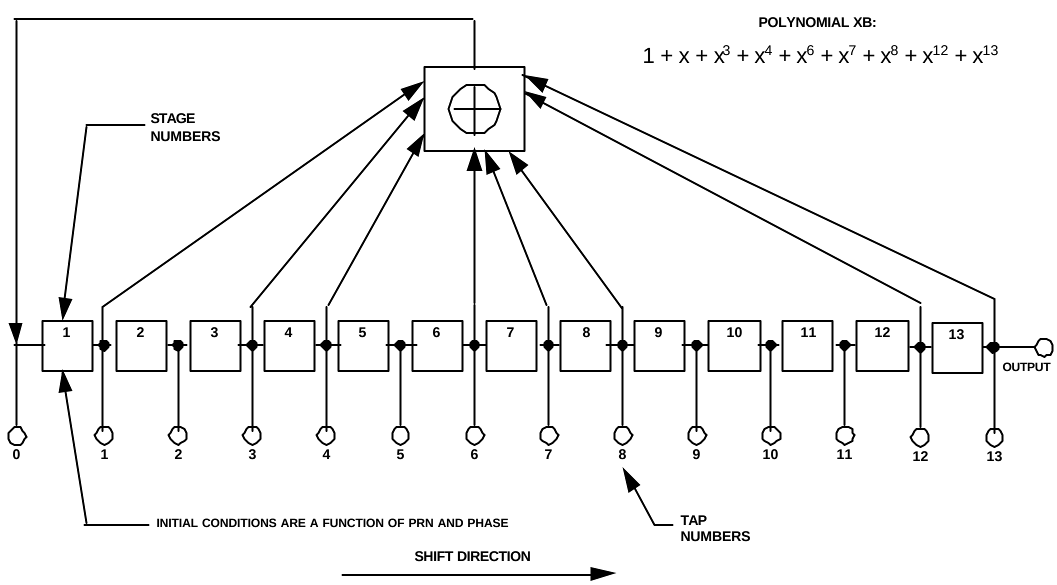
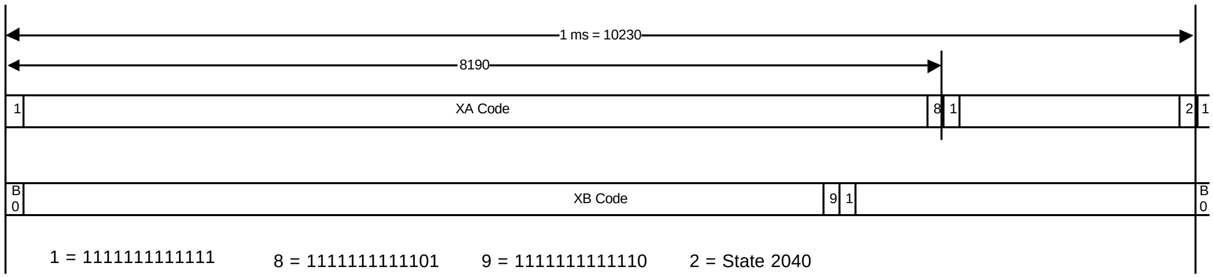
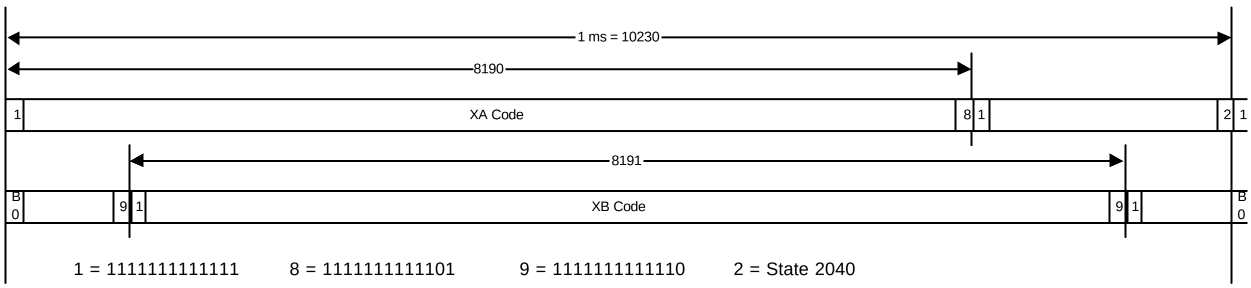


Figure 3-4. XB Shift Register Generator Configuration

The natural 8191 chips of the XA sequence is shortened to 8190 chips to cause precession of the second XA sequence with respect to the natural 8191 chip XB sequence, as shown in Figure 3-5. Re-initialization of the XA shift register produces a 10,230-chip sequence by omitting the last 6151 chips of the second natural XA sequence, or reinitializing to all 1s at the 1 ms epoch. The XB shift register is simply allowed to run its natural course until the next 1 ms epoch when it is reinitialized at its initial state, B0, based upon PRN number and phase. This results in the phase of the XB sequence leading by one chip during the second XA sequence in the 1-millisecond period. Depending upon the initial state of the XB sequence, a third 8191 chip sequence may be started before the 10,230-chip sequence is completed. Two different scenarios that may result are shown in Figure 3-5.



a) B0 = Initial State at 1 ms (less than State 6152)



b) B0 = Initial State at 1 ms (greater than State 6151)

Figure 3-5. Relative Phases Between the XA and XB Sequences

In scenario a, the initial state of the XB sequence, B0, is less than State 6152. Thus, the second natural XB sequence does not run to completion prior to the next 1 ms epoch. In scenario b, the initial state of the XB sequence, B0, is greater than State 6151. Thus, the second natural XB sequence runs to completion and a third natural sequence starts (except when B0 is State 6152) prior to the next 1 ms epoch.

3.3.2.3 Q5 Synchronization Sequence

Each of the 1 ms Q5 code blocks are further encoded with a 20-bit Neuman-Hoffman code. The 20 bits are Modulo-2 added to the code chips at the PRN code epoch rate of 1 kHz. The code, nh20(t), starting coincident with the 20 ms data epoch on the I5 channel, is as follows:

$$nh20(t) = 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0\ 0\ 1\ 1\ 1\ 0$$

3.3.3 Navigation Data

The content and format of the NAV data for data ID number 2 are given in Appendix I of this document (reference paragraph 10.3.3.4.1.1). Data ID number 1 is no longer in use.

3.3.3.1 Navigation Data Modulation

The NAV bit train, D(t), is rate 1/2 encoded and, thus, clocked at 100 symbols per second (sps). In addition, the 100 sps symbols are modulated with a 10-bit Neuman-Hoffman code that is clocked at 1 kHz. The resultant symbol sequence is then used to modulate the L5 in-phase carrier and PRN code.

3.3.3.1.1 Forward Error Correction

The NAV bit train, D(t), will always be rate 1/2 convolutional encoded with a Forward Error Correction (FEC) code. Therefore, the symbol rate is 100 sps. The convolutional coding will be constraint length 7, with a convolutional encoder logic arrangement as illustrated in Figure 3-6. The G1 symbol is selected on the output as the first half of a 20-millisecond data bit period coincident with the first bit of the 20-bit Q5 Neuman-Hoffman code.

Six-second navigation messages broadcast by the SV are synchronized with every fourth of the SV's P(Y) code X1 epochs. Although these epochs are not necessarily accessible to the L5 user, they are used within the SV to define GPS Time. However, message synchronization does provide the L5 user an access to the time of every 4^{th} P(Y) code X1 epoch. Thus, herein, reference will continue to be made to these X1 epochs. See ICD-GPS-200C for details.

Because the FEC encoding convolves successive messages, it is necessary to define which transmitted symbol is synchronized to SV time, as follows. The beginning of the first symbol that contains *any* information about the first bit of a message will be synchronized to every fourth X1 epoch. The users' convolutional decoders will introduce a fixed delay that depends on their respective algorithms (usually 5 constraint lengths, or 35 bits), for which they must compensate to determine system time from the received signal. This convolutional decoding delay and the various relationships with the start of the data block transmission and SV time are illustrated in Figure 3-7 for the L5 signal.

3.3.3.1.2 Neuman-Hoffman Code

Each of the 100 sps symbols are further encoded with a 10-bit Neuman-Hoffman code. The 10 bits are Modulo-2 added to the symbols at the PRN code epoch rate of 1 kHz. The code, nh(t), starting at the 100 sps symbol transitions, is as follows:

Symbol = 1: nh(t) = 1111001010
Symbol = 0: nh(t) = 0000110101

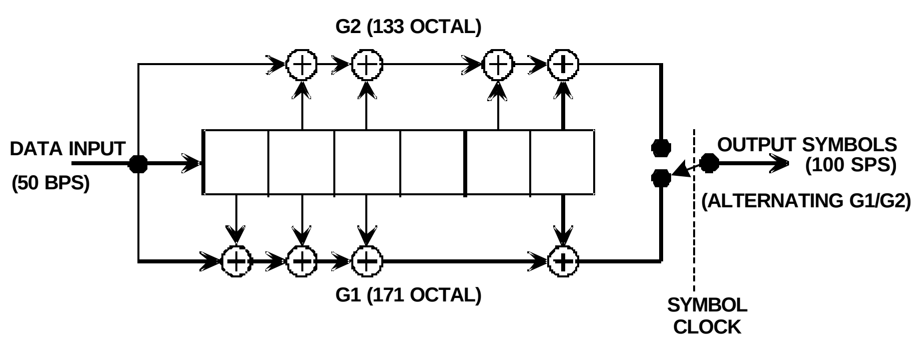


Figure 3-6. Convolutional Encoder

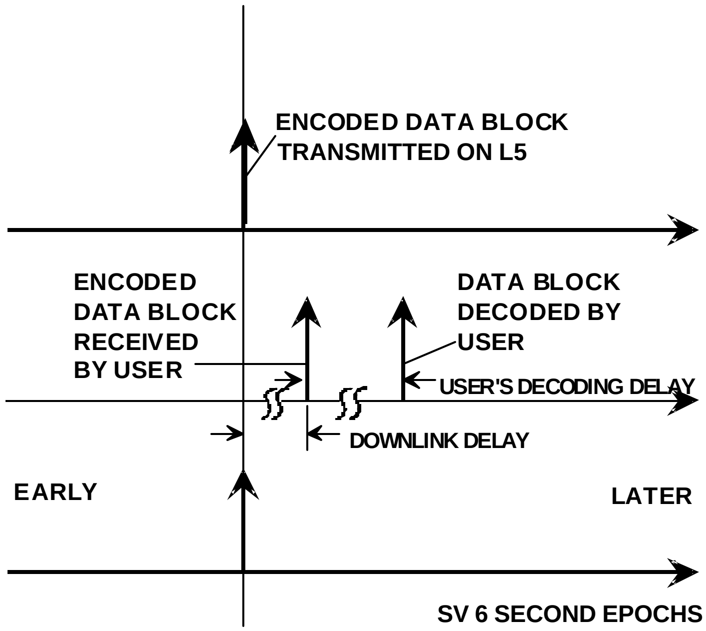


Figure 3-7. Convolutional Transmit/Decoding Timing Relationships

3.3.4 GPS Time and SV Z-Count

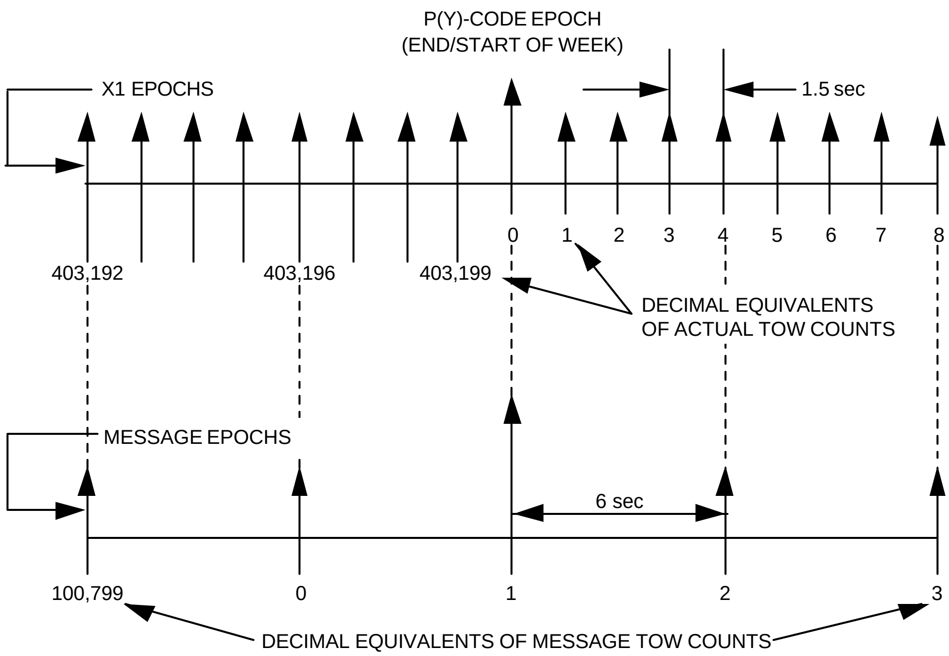
GPS P(Y) and L5 time scales are established by the Operational Control Segment (OCS) and are referenced to a UTC (as maintained by the U.S. Naval Observatory) zero time-point defined as midnight on the night of January 5, 1980/morning of January 6, 1980. GPS Time, as defined in ICD-GPS-200C, is the ensemble of corrected composite L1/L2 P(Y) SV times, corrected via the clock corrections in the L1 and L2 Nav data and the relativity correction. L1/L5 GPS Time will be derived in a similar way, except that it will use the ensemble of corrected composite L1-C/A/L5-Q5 SV times and may therefore be slightly different than GPS Time as defined in ICD-GPS-200C. The largest unit used in stating GPS Time is one week defined as 604,800 seconds, concatenated with the GPS week number. GPS Time may differ from UTC because GPS Time is a continuous time scale, while UTC is corrected periodically with an integer number of leap seconds. There also is an inherent but bounded drift rate between the UTC and GPS time scales. The OCS controls the GPS time scales to be within one microsecond of UTC (Modulo one second).

The L5 NAV data contains the requisite data for relating L1/L5 GPS Time to UTC and L1/L5 GPS Time to GPS Time as defined in ICD-GPS-200C. The accuracy of this data during the transmission interval will be such that it relates L1/L5 GPS Time (maintained by the MCS of the CS) to UTC (USNO) within 90 nanoseconds (one sigma), and to GPS Time as defined in ICD-GPS-200C within TBD nanoseconds. This data is generated by the CS (or provided to the CS); therefore, the accuracy of this relationship may degrade if for some reason the CS is unable to upload data to a SV. At this point, it is assumed that alternate sources of UTC are no longer available, and the relative accuracy of the GPS/UTC relationship will be sufficient for users. Range error components (e.g. SV clock and position) contribute to the GPS time transfer error, and under normal operating circumstances (two frequency time transfers from SV(s) whose navigation message indicates a URA of eight meters or less), this corresponds to a 97 nanosecond (one sigma) apparent uncertainty at the SV. Propagation delay errors and receiver equipment biases unique to the user add to this time transfer uncertainty.

In each SV the X1 epochs of the P(Y)-code offer a convenient unit for precisely counting and communicating time. Time stated in this manner is referred to as Z-count, which is given as a 29-bit binary number consisting of two parts as follows:

a. The binary number represented by the 19 least significant bits of the Z-count is referred to as the time of week (TOW) count and is defined as being equal to the number of X1 epochs that have occurred since the transition from the previous week. The count is short-cycled such that the range of the TOW-count is from 0 to 403,199 X1 epochs (equaling one week) and is reset to zero at the end of each week. The TOW-count's zero state is defined as that X1 epoch which is coincident with the start of the present week. This epoch occurs at (approximately) midnight Saturday night-Sunday morning, where midnight is defined as 0000 hours on the Universal Coordinated Time (UTC) scale that is nominally referenced to the Greenwich Meridian. Over the years the occurrence of the "zero state epoch" may differ by a few seconds from 0000 hours on the UTC scale since UTC is periodically corrected with leap seconds while the TOW-count is continuous without such correction. A truncated version of the TOW-count, consisting of its 17 most significant bits, is contained in each of the six-second messages of the L5 downlink data stream; the relationship between the actual TOW-count and its truncated message version is illustrated by Figure 3-8.

b. The ten most significant bits of the Z-count are a Modulo 1024 binary representation of the sequential number assigned to the current GPS week (see paragraph 4.2.4). The range of this count is from 0 to 1023 with its zero state being defined as the GPS week number zero and every integer multiple of 1024 weeks, thereafter (i.e., 0, 1024, 2048, etc.).



NOTES:

1. THE TOW COUNT APPEARS IN EACH 6-SECOND MESSAGE
2. THE 6-SECOND MESSAGE TOW COUNT CONSISTS OF THE 17 MSBs OF THE ACTUAL TOW COUNT AT THE START OF THE NEXT MESSAGE.
3. TO CONVERT FROM THE MESSAGE TOW COUNT TO THE ACTUAL TOW COUNT AT THE START OF THE NEXT MESSAGE, MULTIPLY BY FOUR.

<u>Figure 3-8.</u> Time Line Relationship of A Six-Second Message

4 Notes

4.1 Acronyms

Autonav	Autonomous Navigation
BPSK	Bi-Phase Shift Key
CS	Control Segment
DN	Day Number
ECEF	Earth-Centered Earth-Fixed
ECI	Earth-Centered Inertial
GPS	Global Positioning System
ICD	Interface Control Document
ID	Identification
IERS	International Earth Rotation Service
IODC	Issue of Data, Clock
IODE	Issue of Data, Ephemeris
IRM	IERS Reference Meridian
IRP	IERS Reference Pole
LSB	Least Significant Bit
LSF	Leap Seconds Future
MCS	Master Control Station
MSB	Most Significant Bit
NAV	Navigation
OCS	Operational Control Segment
PRN	Pseudo-Random Noise
RF	Radio Frequency
RMS	Root Mean Square
SA	Selective Availability
SS	Space Segment
SV	Space Vehicle
SVN	Space Vehicle Number
TBD	To Be Determined
TBS	To Be Supplied
TBR	To Be Reviewed
TOW	Time Of Week
URA	User Range Accuracy
URE	User Range Error
US	User Segment
USNO	U.S. Naval Observatory
UTC	Universal Coordinated Time
WGS 84	World Geodetic System 1984
WN	Week Number

4.2 Definitions

4.2.1 User Range Accuracy

User range accuracy (URA) is a statistical indicator of the ranging accuracy obtainable with a specific SV and a specific ranging signal or signals. L5 URA (URA_5) is greater than or equal to a one-sigma estimate of the user range errors in the L5 navigation data for the transmitting satellite. It includes ephemeris and clock errors resulting after the corrections specified in Section 10.3 for the L5 or L1/L5 user are applied. It does not include any errors introduced in the user set or the transmission media. While the URA_5 may vary over a given message fit interval, the URA_5 index (N) reported in the NAV message corresponds to the maximum value of URA_5 anticipated over the fit interval.

4.2.2 SV Block Definitions

The following block definitions are given to facilitate discussion regarding the capability of the various blocks of GPS satellites to support the SV-to-US interface.

4.2.2.1 Developmental SVs

The original concept validation satellites developed by Rockwell International and designated as satellite vehicle numbers (SVNs) 1-11 are termed "Block I" SVs. These SVs were designed to provide 3-4 days of positioning service without contact from the CS. There are no longer any active Block I SVs in the GPS Constellation. The last Block I SV was decommissioned in 1995.

4.2.2.2 Operational SVs

Previous blocks of operational satellites are designated Block II, Block IIA and Block IIR SVs. Characteristics of these SVs are provided below. These SVs all transmit a configuration code of 001 (reference 10.3.3.4.1.5). The navigation signal provides no direct indication of the type of the transmitting SV.

4.2.2.2.1 Block II SVs

The first block of full scale operational SVs developed by Rockwell International are designated as SVNs 13-21 and are termed "Block II" SVs. These SVs were designed to provide 14 days of positioning service without contact from the CS. These satellites do not broadcast the L5 signal.

4.2.2.2.2 Block IIA SVs

The second block of full scale operational SVs developed by Rockwell International are designated as SVNs 22-40 and are termed "Block IIA" SVs. These SVs were designed to provide 180 days of positioning service without contact from the CS. These satellites do not broadcast the L5 signal.

4.2.2.2.3 Block IIA SVs

The second block of full scale operational SVs developed by Rockwell International are designated as SVNs 22-40 and are termed "Block IIA" SVs. These SVs were designed to provide 180 days of positioning service without contact from the CS. These satellites do not broadcast the L5 signal.

4.2.2.2.4 Block IIR SVs

The block of operational replenishment SVs developed by Martin Marietta are designated as SVNs 41-66 and are termed “Block IIR” SVs. These SVs will provide at least 14 days of positioning service without contact from the CS when the SVs are operating in the Block IIA mode and will provide a minimum of 180 days of positioning service without contact from the CS when operating in autonomous navigation (Autonav) mode. These satellites do not broadcast the L5 signal.

4.2.2.3 Block IIF Operational SVs

The Block IIF operational SVs do broadcast the L5 signal. Paragraph 4.2.3 may not apply.

Note: *This paragraph will be updated, based on an anticipated update of ICD-GPS-200C.*

4.2.3 Operational Interval Definitions

The following three operational intervals have been defined. These labels will be used to refer to differences in the interface definition as time progresses from SV acceptance of the last navigation data upload.

4.2.3.1 Normal Operations

The SV is undergoing normal operations whenever the fit interval flag (reference paragraph 10.3.3.2.3.1) is zero.

4.2.3.2 Short-term Extended Operations

The SV is undergoing short-term extended operations whenever the fit interval flag is one and the IODE (reference paragraph 10.3.4.4) is less than 240.

4.2.3.3 Long-term Extended Operations

The SV is undergoing long-term extended operations whenever the fit interval flag is one and the IODE is in the range 240-255.

Note: *The DoD Navigation User Segment and Time Transfer User have no requirement to operate, and may not operate properly, whenever any SV is operating in long-term extended operations.*

4.2.4 GPS Week Number

The GPS week numbering system is established with week number zero (0) being defined as that week which started with the X1 epoch occurring at midnight UTC(USNO) on the night of January 5, 1980/morning of January 6, 1980. The GPS week number continuously increments by one (1) at each end/start of week epoch without ever resetting to zero. Users must recognize that the week number information contained in the Nav

Messages may not necessarily reflect the current full GPS week number (see paragraphs 10.3.3.1.1.1, 10.3.3.3.1.1, and 10.3.3.3.2.1).

4.3 Supporting Material

4.3.1 L5 Received Signals

The guaranteed minimum user-received L5 signal levels are defined in paragraph 3.3.1.6.

Figure 4-1. User Received Minimum Signal Levels

(To be supplied by the spacecraft manufacturer)

Note: *The minimum received signal power for L5 shall be –154 dBW. This paragraph and figure callout are placeholders for information on minimum received signal power versus elevation angle for GPS L5. This information is satellite dependent, and will be supplied by the spacecraft manufacturer once they have completed their design.*

10 Appendix I. GPS Navigation Data Structure for Data ID No. 2

Note: The jump in section numbers and unusual section title is to maintain consistency with DoD ICD conventions. See the note in Section 1.2.

10.1 Scope

This appendix describes the specific GPS navigation (NAV) data structure denoted by data ID number 2. This data ID number, when transmitted as part of the NAV data, is represented by the two-bit binary notation as 01. Data ID number 1 is no longer in use.

10.2 Applicable Documents

None.

10.3 Requirements

10.3.1 Data Characteristics

The L5 channel data stream mostly contains the same data as the L1 and L2 channels, but in an entirely different format. Also, the L5 data stream uses a different parity algorithm.

10.3.2 Message Structure

As shown in Figures 10-1 through 10-5, the L5 message structure utilizes a basic format of six-second 300-bit long messages. In addition, each message contains a CRC parity block consisting of 24 bits covering the entire six-second message (300 bits) (reference Section 10.3.5 - TBR). At present, there are only 5 message types out of 64 possible types.

10.3.3 Message Content

As shown in Figures 10-1 through 10-5, the L5 message structure utilizes a basic format of six-Each message starts with an 8-bit preamble – 10001011, followed by a 6-bit message type ID and the 17-bit message time of week (TOW) count. When the value of the message TOW count is multiplied by 6, it represents SV time in seconds at the start of the next 6-second message. An "alert" flag, when raised (bit 32 = "1"), indicates to the user that the SV URA_5 may be worse than indicated in Message Type 1, and the SV should be used at the user's own risk. A 6-bit PRN number, with a range of 1 to 37, starts at bit 33 of Message Types 1, 3, 4 and 5.

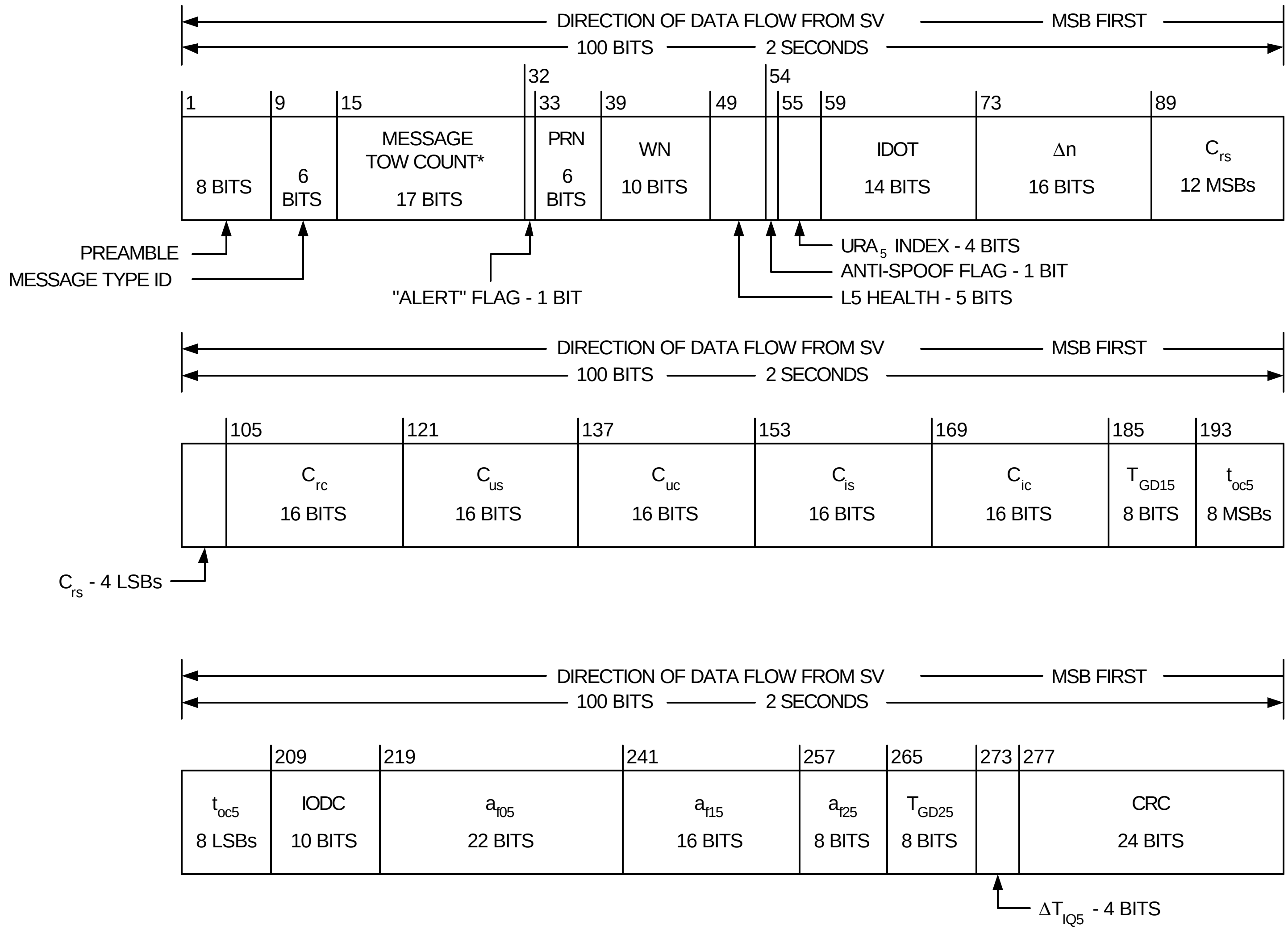
10.3.3.1 Message Type 1 Clock, Health, and Accuracy Parameters

10.3.3.1.1 Message Type 1 Clock, Health, and Accuracy Parameter Content

The clock parameters in Message Type 1 describe the SV time scale during the period of validity. The parameters in a data set are valid during the interval of time in which they are transmitted and will remain valid for an additional period of time after transmission of the next data set has started.

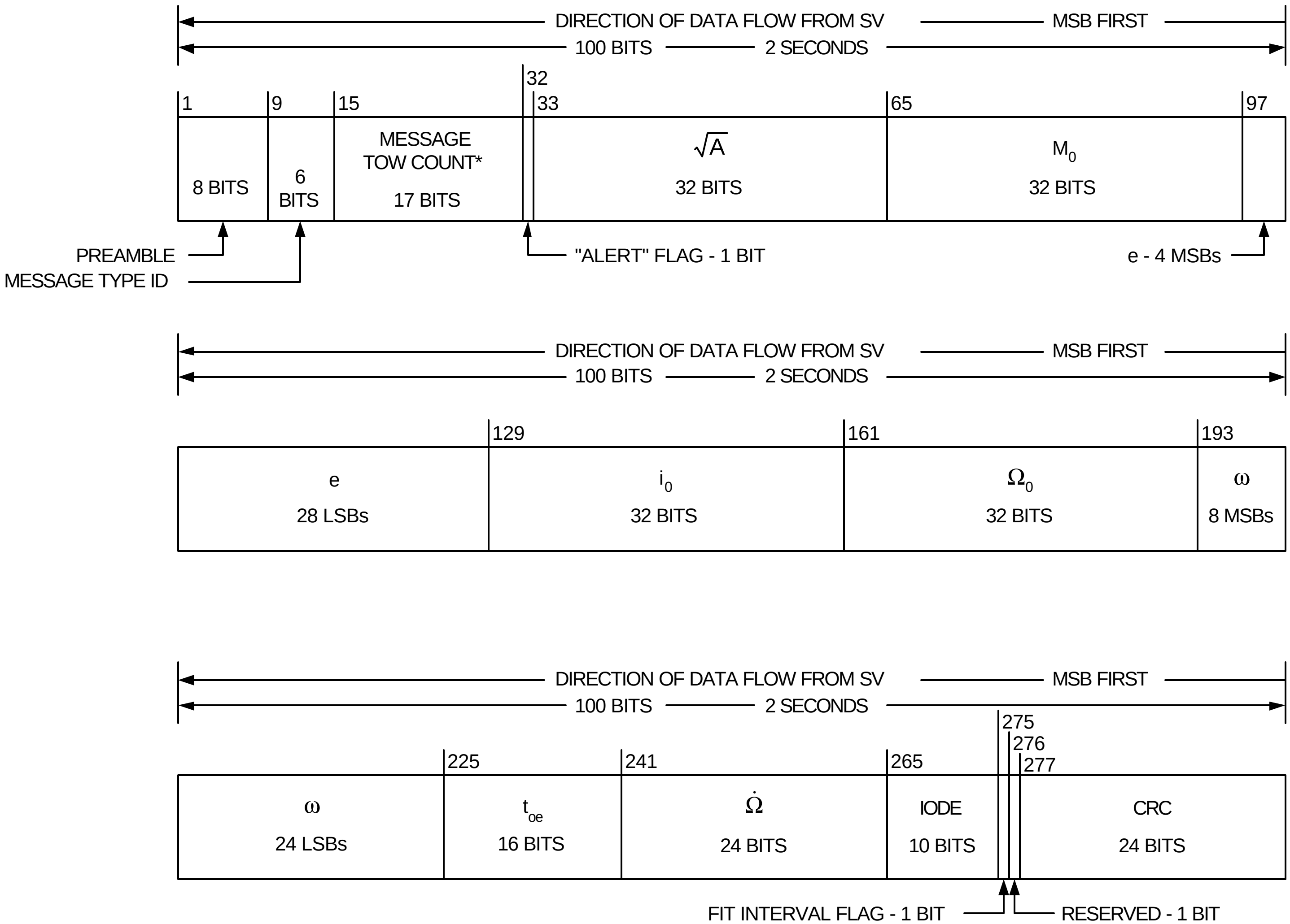
10.3.3.1.1.1 Transmission Week Number

The ten bits starting at bit 39 contain the ten MSBs of the 29-bit Z-count as qualified herein. These ten bits are a Modulo 1024 binary representation of the current GPS week number at the start of the data set transmission interval (see paragraph 3.3.4(b)). The GPS week number increments at each end/start of week epoch. For Block II SVs in long-term extended operations, beginning approximately 28 days after upload, the transmission week number may not correspond to the actual GPS week number due to curve fit intervals that cross week boundaries.



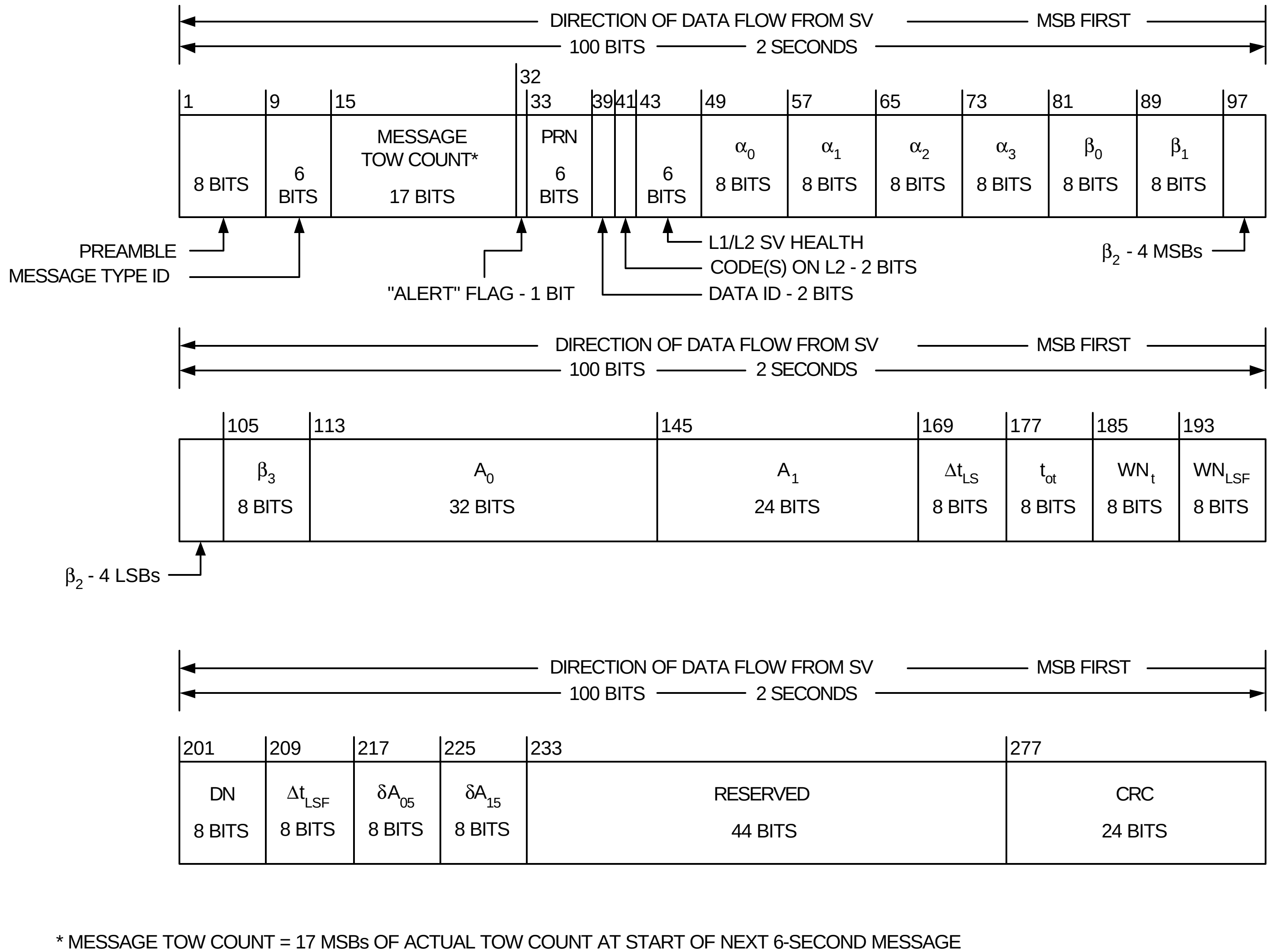
* MESSAGE TOW COUNT = 17 MSBs OF ACTUAL TOW COUNT AT START OF NEXT 6-SECOND MESSAGE

Figure 10-1. Message Type 1 Format

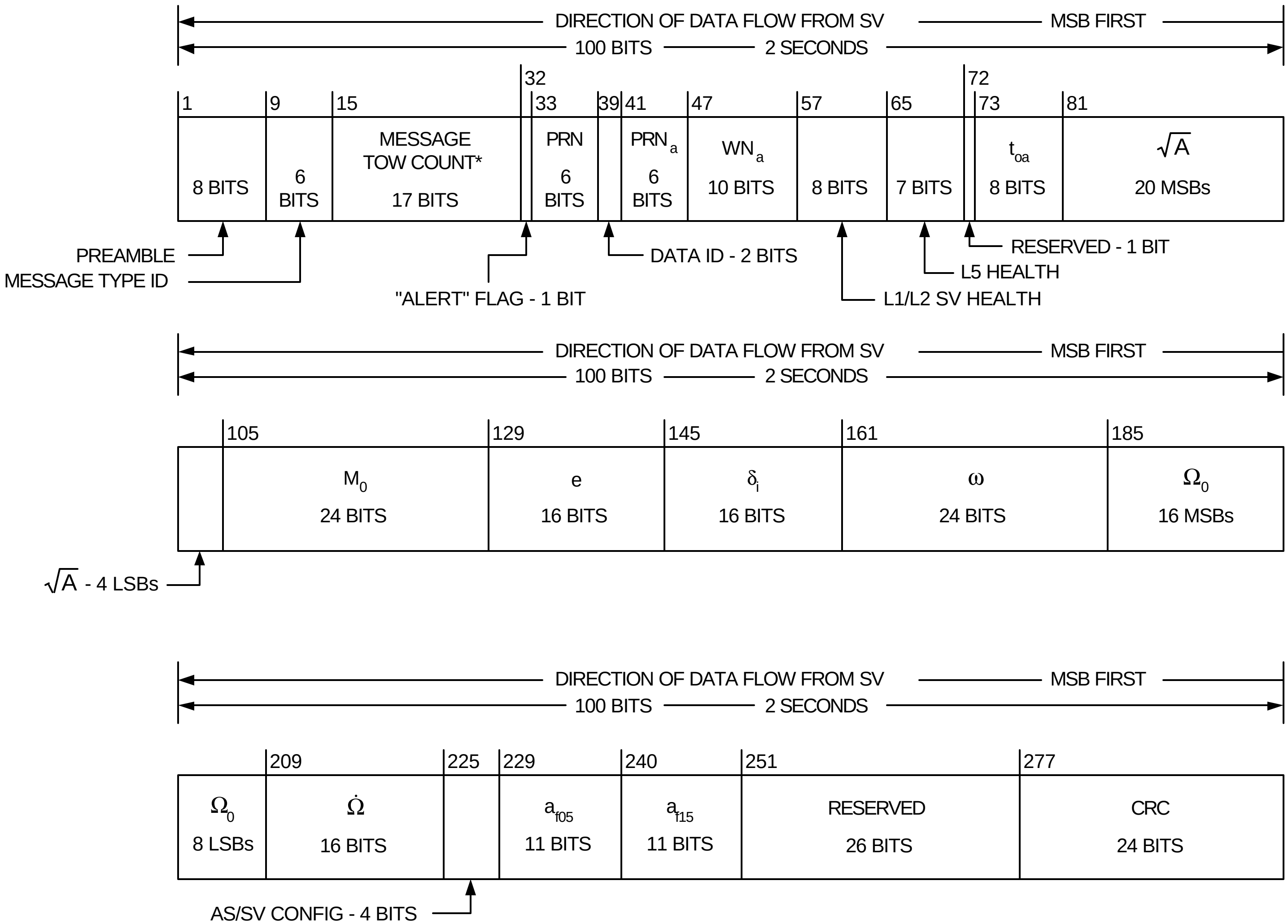


* MESSAGE TOW COUNT = 17 MSBs OF ACTUAL TOW COUNT AT START OF NEXT 6-SECOND MESSAGE

Figure 10-2. Message Type 2 Format

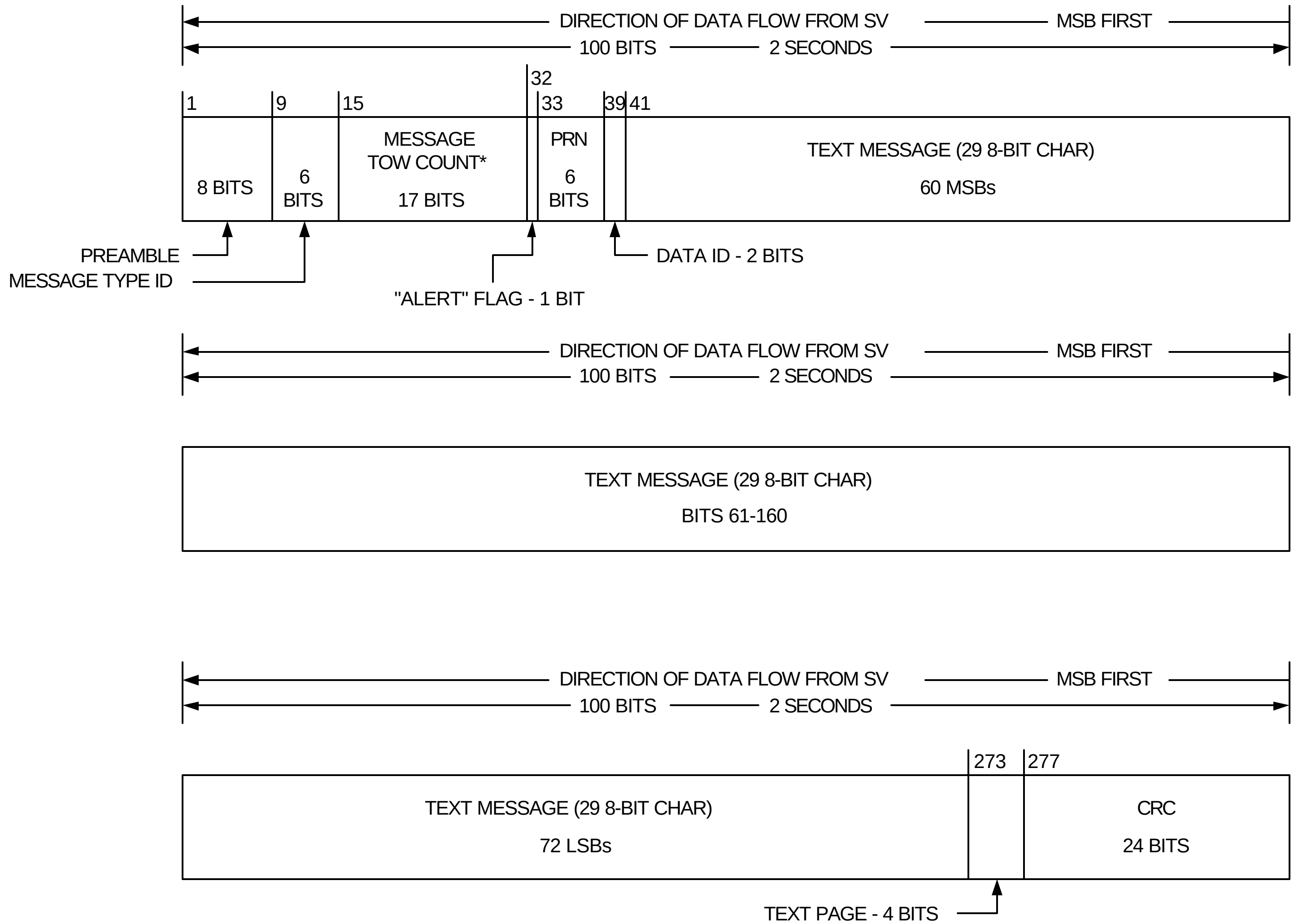


<u>Figure 10-3.</u> Message Type 3 Format



* MESSAGE TOW COUNT = 17 MSBs OF ACTUAL TOW COUNT AT START OF NEXT 6-SECOND MESSAGE

Figure 10-4. Message Type 4 Format



* MESSAGE TOW COUNT = 17 MSBs OF ACTUAL TOW COUNT AT START OF NEXT 6-SECOND MESSAGE

Figure 10-5. Message Type 5 Format

10.3.3.1.1.2 SV Accuracy (L5)

Bits 55 through 58 contain the URA_5 index of the SV (reference paragraph 4.2.1) for the unauthorized (non-Precise Positioning Service) user. The URA_5 index (N) is an integer in the range of 0 through 15 and has the following relationship to the URA_5 of the SV:

URA_5 INDEX	URA_5 (meters)		
0	0.00	$< URA_5 \leq$	2.40
1	2.40	$< URA_5 \leq$	3.40
2	3.40	$< URA_5 \leq$	4.85
3	4.85	$< URA_5 \leq$	6.85
4	6.85	$< URA_5 \leq$	9.65
5	9.65	$< URA_5 \leq$	13.65
6	13.65	$< URA_5 \leq$	24.00
7	24.00	$< URA_5 \leq$	48.00
8	48.00	$< URA_5 \leq$	96.00
9	96.00	$< URA_5 \leq$	192.00
10	192.00	$< URA_5 \leq$	384.00
11	384.00	$< URA_5 \leq$	768.00
12	768.00	$< URA_5 \leq$	1536.00
13	1536.00	$< URA_5 \leq$	3072.00
14	3072.00	$< URA_5 \leq$	6144.00
15	6144.00	$< URA_5$ (or no accuracy prediction is available – users are advised to use the SV at their own risk.)	

For each URA_5 index (N), users may compute a nominal URA_5 value (X) as given by:

- If the value of N is 6 or less, $X = 2^{(1 + N/2)}$,
- If the value of N is 6 or more, but less than 15, $X = 2^{(N - 2)}$,
- N = 15 indicates the absence of an accuracy prediction and advises the unauthorized user to use that SV at his own risk.

For N = 1, 3, and 5, X should be rounded to 2.8, 5.7, and 11.3 meters, respectively.

10.3.3.1.1.3 SV Health (L5)

The five-bit health indication in bits 49 through 53 refers to the transmitting SV for the L5 signal. The MSB indicates a summary of the health of the NAV data, where

0 = all NAV data are OK,

1 = some or all NAV data are bad.

The four LSBs indicate the health of the L5 signal components in accordance with the codes given in paragraph 10.3.3.4.1.4. The health indication is given relative to the "as designed" capabilities of each SV (as designated by the configuration code – see paragraph 10.3.3.4.1.5). Accordingly, any SV that does not have a certain capability will be indicated as "healthy" if the lack of this capability is inherent in its design or if it has been configured into a mode that is normal from a user standpoint and does not require that capability.

Additional SV health data are given in Message Type 4, the Almanac message. The data given in Message Type 1 may differ from that shown in Message Type 4 on other SVs since the latter may be updated at a different time.

10.3.3.1.1.4 Issue of Data, Clock

Bits 209 through 218 contain the IODC. The IODC indicates the issue number of the data set and thereby provides the user with a convenient means of detecting any change in the correction parameters. Constraints on the IODC as well as the relationship between the IODC and the IODE (issue of data, ephemeris) terms are defined in paragraph 10.3.4.4.

10.3.3.1.1.5 Short-term and Long-term Extended Operations

Whenever the fit interval flag indicates a fit interval greater than 4 hours, the IODC can be used to determine the actual fit interval of the data set (reference section 10.3.4.4).

10.3.3.1.1.6 SV Clock Correction

Message Type 1 contains the parameters needed by the users for apparent SV L1/L5 clock correction (t_{oc5}, a_{25}, a_{15}, a_{05}). The related algorithm is given in paragraph 10.3.3.1.3.1.

10.3.3.1.1.7 Estimated Group Delay Differential (L1-L5)

The L1-L5 correction term in Message Type 1, T_{GD15}, is for the benefit of "L1-C/A only" or "L5-Q5 only" users; the related user algorithm is given in paragraph 10.3.3.1.3.2.

10.3.3.1.1.8 Estimated L2/L5 Group Delay Differential

The L2/L5 group delay correction term, T_{GD25}, for the benefit of single frequency L2-C/A users and dual frequency L2/L5 users is contained in Message Type 1; the related user algorithms are given in paragraphs 10.3.3.1.3.3 and 10.3.3.1.3.5.

10.3.3.1.1.9 Estimated L5 Q5/I5 Group Delay Differential

The L5 I5-code/Q5-code group delay correction term, ΔT_{IQ5}, for the benefit of L5 users tracking the I5 code is contained in Message Type 1; the related user algorithms are given in paragraphs 10.3.3.1.3.3 and 10.3.3.1.3.5.

10.3.3.1.2 Message Type 1 Clock, Health and Accuracy Parameter Characteristics

For those parameters whose characteristics are not fully defined in Section 10.3.3.1.1, the number of bits, the scale factor of the LSB (which is the last bit received), the range, and the units are as specified in Table 10-I.

10.3.3.1.3 User Algorithms for Message Type 1 Clock Data

The algorithms defined below (a) allow all users to correct the code phase time received from the SV with respect to both SV code phase offset and relativistic effects, (b) permit the "single frequency" (L1-C/A, L2-C/A or L5) user, "dual L1 and L5 frequency," and "dual L2 and L5 frequency" user to compensate for the effects of SV group delay differential (the user who utilizes both the L1-C/A and L5-Q5 frequencies does not require this correction, since the clock parameters account for the induced effects), and (c) allow the user of the L5 I5-code to correct for the timing error between the I5 and Q5 codes. Those users who utilize the "dual L1 and L2 frequencies" shall use the corrections provided in the L1 or L2 NAV messages.

10.3.3.1.3.1 User Algorithms for SV Clock Correction

The polynomial defined in the following allows the user to determine the effective SV PRN code phase offset referenced to the phase center of the antennas (Δt_{sv}) with respect to GPS L5 system time (t) at the time of data transmission. The coefficients transmitted in Message Type 1 describe the offset apparent to the two-frequency (L1 and L5) user for the interval of time in which the parameters are transmitted. This estimated correction accounts for the deterministic SV clock error characteristics of bias, drift and aging, as well as for the SV implementation characteristics of group delay bias and mean differential group delay. Since these coefficients do not include corrections for relativistic effects, the user's equipment must determine the requisite relativistic correction. Accordingly, the offset given below includes a term to perform this function.

The user shall correct the time received from the SV with the equation (in seconds)

$$t = t_{sv} - \Delta t_{sv} \tag{1}$$

where

t = GPS L5 system time (seconds),

t_{sv} = effective SV PRN code phase time at message transmission time (seconds),

Δt_{sv} = SV PRN code phase time offset (seconds).

Table 10-I. Message Type 1 Clock, Health and Accuracy Parameters				
Parameter	No. of Bits**	Scale Factor (LSB)	Effective Range***	Units
Week No.	10	1		Weeks
SV accuracy (URA)	4			(see text)
SV health (L5)	6	1		discrete
T_{GD15}	8*	2^{-31}		seconds
T_{GD25}	8*	2^{-31}		seconds
ΔT_{IQ5}	4*	2^{-31}		seconds
IODC	10			(see text)
t_{oc5}	16	2^{4}	604,784	seconds
a_{f25}	8*	2^{-55}		sec/sec^2
a_{f15}	16*	2^{-43}		sec/sec
a_{f05}	22*	2^{-31}		seconds

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB.

** See Figure 10-1 for complete bit allocation in Message Type 1.

*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

The SV PRN code phase offset is given by

$$\Delta t_{sv} \quad = \quad a_{f05} + a_{f15}(t - t_{oc5}) + a_{f25}(t - t_{oc5})^2 + \Delta t_r \qquad (2)$$

where

a_{f05}, a_{f15} and a_{f25} are the polynomial coefficients given in Message Type 1, t_{oc5} is the clock data reference time in seconds (reference paragraph 10.3.4.5), and Δt_r is the relativistic correction term (seconds) which is given by

$$\Delta t_r \quad = \quad Fe(A)^{1/2} \sin E_k.$$

The orbit parameters (e, A, E_k) used here are described in discussions of data contained in Message Type 2, while F is a constant whose value is

$$F = \frac{-2\mu^{1/2}}{c^2} = -4.442807633\ (10)^{-10}\ \ \text{sec/(meter)}^{1/2},$$

where

$$\mu = 3.986005 \times 10^{14}\ \frac{\text{meters}^3}{\text{second}^2} \quad = \quad \text{value of Earth's universal gravitational parameter}$$

$$c = 2.99792458 \times 10^8\ \frac{\text{meters}}{\text{second}} \quad = \quad \text{speed of light.}$$

Note that equations (1) and (2), as written, are coupled. While the coefficients a_{f05}, a_{f15} and a_{f25} are generated by using GPS time as indicated in equation (2), sensitivity of t_{sv} to t is negligible. This negligible sensitivity will allow the user to approximate t by t_{SV} in equation (2). The value of t must account for beginning or end of week crossovers. That is, if the quantity t - t_{oc5} is greater than 302,400 seconds, subtract 604,800 seconds from t. If the quantity t - t_{oc5} is less than -302,400 seconds, add 604,800 seconds to t.

The control segment will utilize the following alternative but equivalent expression for the relativistic effect when estimating the NAV parameters:

$$\Delta t_r = -\frac{2\,\vec{R}\bullet\vec{V}}{c^2}$$

where

$\vec{R}$ is the instantaneous position vector of the SV,

$\vec{V}$ is the instantaneous velocity vector of the SV, and
c is the speed of light. (Reference paragraph 10.3.4.3).

It is immaterial whether the vectors $\vec{R}$ and $\vec{V}$ are expressed in earth-fixed, rotating coordinates or in earth-centered, inertial coordinates.

Since the SV clock corrections of equations (1) and (2) are estimated by the CS using dual frequency L1 and L5 measurements, the single-frequency L5 user and the dual frequency L2/L5 user must apply additional terms to equations (1) and (2). These terms are described in paragraphs 10.3.3.1.3.2 and 10.3.3.1.3.3.

10.3.3.1.3.2 L1/L5 Correction

The L1 and L5 correction term, T_{GD15}, is monitored to account for the effect of SV group delay differential between L1 C/A code and L5 Q5 code. The value for T_{GD15} is based on measurements made by the SV contractor during factory testing *and continued estimation*. This correction term is only for the benefit of "single-frequency" (L1 or L5) users; it is necessitated by the fact that the SV clock offset estimates reflected in the a_{f05} clock correction coefficient (see paragraph 10.3.3.1.3.1) are based on the effective PRN code phase as apparent with two frequency ionospheric corrections. Thus, the user who utilizes the L1 frequency only must modify the code phase offset in accordance with paragraph 10.3.3.1.3.1 with the equation

$$(\Delta t_{SV})_{L1} = \Delta t_{SV} - T_{GD15}$$

where T_{GD15} is provided to the user as Message Type 1 data. For the user who utilizes L5 only, the code phase modification is given by

$$(\Delta t_{SV})_{L5} = \Delta t_{SV} - \gamma_{15} T_{GD15}$$

where, denoting the nominal center frequencies of L1 and L52 as f_{L1} and f_{L5} respectively,

$$\gamma_{15} = (f_{L1}/f_{L5})^2 = (1575.42/1176.45)^2 = (154/115)^2.$$

The value of T_{GD15} is not equal to the mean SV group delay differential, but is equal to the delay differential multiplied by $1/(1-\gamma_{15})$. That is,

$$T_{GD15} = \frac{1}{1-g_{15}}\left(t_{L5} - t_{L1}\right)$$

where t_{Li} is the GPS time the i^{th} frequency signal is transmitted from the SV.

10.3.3.1.3.3 L2/L5 Group Delay Correction

The L2/L5 group delay correction term, T_{GD25}, is calculated by the CS to account for the effect of SV group delay differential between the composite dual frequency L1/L5 time and L2 C/A code time based on measurements made by the SV contractor during factory testing *and continued estimation*. This correction term is for the benefit of all L2-only and L2/L5 users; it is necessitated by the fact that the SV clock offset estimates reflected in the a_{f05} clock correction coefficient (see paragraph 10.3.3.1.3.1) are based on the effective composite L1/L5 measurement as apparent with L1/L5 ionospheric corrections. Thus, the user who utilizes the L2 frequency only must modify the code phase offset in accordance with paragraph 10.3.3.1.3.1 with the equation

$$(\Delta t_{SV})_{L2} = \Delta t_{SV} - T_{GD25}$$

where T_{GD25} is provided to the user as Message Type 1 data. The value of T_{GD25} is not equal to the mean SV group delay differential, but is equal to

$$T_{GD25} = t_{L1} - t_{L2} + T_{GD15}$$

to account for the group delay difference between the L1/L5 and L2 signals.

10.3.3.1.3.4 L1/L5 Ionospheric Correction

The two frequency (L1 C/A-code and L5 Q5-code) user shall correct for the group delay due to ionospheric effects by applying the relationship:

$$PR = \frac{PR_5 - g_{15}\, PR_1}{1 - g_{15}}$$

where

PR = pseudorange corrected for ionospheric effects,
PR_i = pseudorange measured on the L-band channel indicated by the subscript.

and

$$\gamma_{15} = (f_{L1}/f_{L5})^2 = (1575.42/1176.45)^2 = (154/115)^2$$

The clock correction coefficients are based on “two frequency” measurements and therefore account for the effects of mean differential delay in SV instrumentation.

10.3.3.1.3.5 L2/L5 Ionospheric Correction

The two frequency (L2 and L5) user shall correct for the group delay due to ionospheric effects by applying the relationship:

$$PR = \frac{(PR_2 - cT_{GD25}) - \gamma_{25}(PR_5 - cT_{GD15})}{1 - \gamma_{25}}$$

where

$$\gamma_{25} = (f_{L2}/f_{L5})^2 = (1227.6/1176.45)^2 = (24/23)^2$$

This additional correction for the dual frequency L2/L5 users is due to the fact that the SV clock offset estimates reflected in the clock correction coefficients (see paragraph 10.3.3.1.3.1) are based on the effective PRN code phase as apparent with two frequency (L1/L5) ionospheric corrections, not the two frequency (L2/L5) ionospheric corrections.

10.3.3.1.3.6 L5 Q-code/I-code Correction

The L5 Q-code/I-code group delay correction term, ΔT_{IQ5}, is calculated by the CS to account for the effect of SV group delay differential between the L5 Q-code and L5 I-code based on measurements made by the SV contractor during factory testing *and continued estimation*. It is defined such as to be positive when the I-code transitions lead the Q-code transitions, and negative when the I-code transitions lag the Q-code transitions.

10.3.3.1.3.7 Example Application of Correction Parameters

A typical system application of the correction parameters for a user receiver is shown in Figure 10-6. The ionospheric model referred to in Figure 10-6 is discussed in paragraph 10.3.3.3.2.2 in conjunction with the related data contained in Message Type 3.

10.3.3.2 Message Type 1 and 2 Ephemeris Parameters

10.3.3.2.1 Message Type 1 and 2 Ephemeris Parameter Content

The contents of the ephemeris representation parameters in Message Types 1 and 2 are defined below, followed by material pertinent to the use of the data.

The ephemeris parameters describe the orbit of the transmitting SV during the curve fit intervals described in section 10.3.4. Table 10-II gives the definition of the orbital parameters using terminology typical of Keplerian orbital parameters; it is noted, however, that the transmitted parameter values are expressed such that they provide the best trajectory fit in Earth-Centered, Earth-Fixed (ECEF) coordinates for each specific fit interval. The user shall not interpret intermediate coordinate values as pertaining to any conventional coordinate system.

The issue of ephemeris data (IODE) term provides the user with a convenient means for detecting any change in the ephemeris representation parameters. The IODE is provided in Message Type 2 for the purpose of comparison with the 10 bits of the IODC term in Message Type 1. Whenever these two terms do not match, a data set cutover has occurred and new data must be collected. The timing of the IODE and constraints on the IODC and IODE are defined in paragraph 10.3.4.4.

Any change in the Message Type 1 and 2 data will be accomplished with a simultaneous change in both the IODC and IODE words. The CS will assure that the t_{oe} value, for at least the first data set transmitted by an SV after an upload, is different from that transmitted prior to the cutover.

A "fit interval" flag is provided in Message Type 2 to indicate whether the ephemerides are based on a four-hour fit interval or a fit interval greater than four hours (reference paragraph 10.3.3.2.3.1).

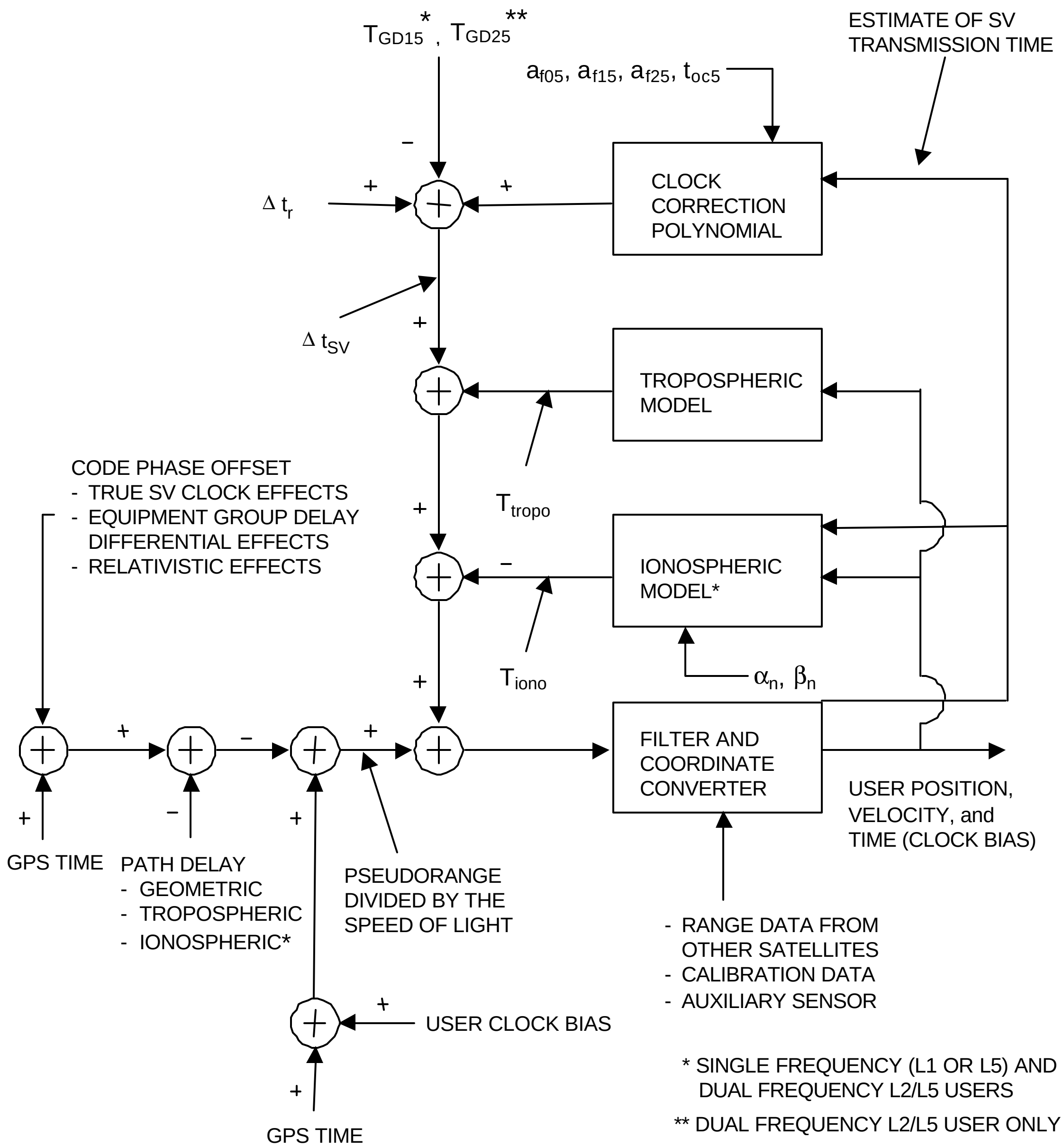


Figure 10-6. **Sample Application of Correction Parameters**

Table 10-II. Ephemeris Data Definitions

M_0	Mean Anomaly at Reference Time
Δn	Mean Motion Difference From Computed Value
e	Eccentricity
$(A)^{1/2}$	Square Root of the Semi-Major Axis
$(OMEGA)_0$	Longitude of Ascending Node of Orbit Plane at Weekly Epoch
i_0	Inclination Angle at Reference Time
ω	Argument of Perigee
OMEGADOT	Rate of Right Ascension
IDOT	Rate of Inclination Angle
C_{uc}	Amplitude of the Cosine Harmonic Correction Term to the Argument of Latitude
C_{us}	Amplitude of the Sine Harmonic Correction Term to the Argument of Latitude
C_{rc}	Amplitude of the Cosine Harmonic Correction Term to the Orbit Radius
C_{rs}	Amplitude of the Sine Harmonic Correction Term to the Orbit Radius
C_{ic}	Amplitude of the Cosine Harmonic Correction Term to the Angle of Inclination
C_{is}	Amplitude of the Sine Harmonic Correction Term to the Angle of Inclination
t_{oe}	Reference Time Ephemeris (reference paragraph 10.3.4.5)
IODE	Issue of Data (Ephemeris)

10.3.3.2.2 Message Type 1 and 2 Ephemeris Parameter Characteristics

For each ephemeris parameter contained in Message Types 1 and 2, the number of bits, the scale factor of the LSB (which is the last bit received), the range, and the units are as specified in Table 10-III.

10.3.3.2.3 User Algorithm for Ephemeris Determination

The user shall compute the ECEF coordinates of position for the phase center of the SVs' antennas utilizing a variation of the equations shown in Table 10-IV. The ephemeris parameters are Keplerian in appearance; the values of these parameters, however, are produced by the CS via a least squares curve fit of the predicted ephemeris of the phase center of the SVs' antennas (time-position quadruples; t, x, y, z expressed in ECEF coordinates). Particulars concerning the periods of the curve fit, the resultant accuracy, and the applicable coordinate system are given in the following subparagraphs.

10.3.3.2.3.1 Curve Fit Intervals

The "fit interval" flag which indicates the curve-fit interval used by the CS in determining the ephemeris parameters, as follows:

0 = 4 hours,
1 = greater than 4 hours.

The relationship of the curve-fit interval to transmission time and the timing of the curve-fit intervals is covered in section 10.3.4.

Table 10-III. Ephemeris Parameters

Parameter	No. of Bits**	Scale Factor (LSB)	Effective Range***	Units
IODE	10			(see text)
C_{rs}	16*	2^{-5}		meters
Δn	16*	2^{-43}		semi-circles/sec
M_0	32*	2^{-31}		semi-circles
C_{uc}	16*	2^{-29}		radians
E	32	2^{-33}	0.03	dimensionless
C_{us}	16*	2^{-29}		radians
$(A)^{1/2}$	32	2^{-19}		$\text{meters}^{1/2}$
t_{oe}	16	2^{4}	604,784	seconds
C_{ic}	16*	2^{-29}		radians
$(OMEGA)_0$	32*	2^{-31}		semi-circles
C_{is}	16*	2^{-29}		radians
i_0	32*	2^{-31}		semi-circles
C_{rc}	16*	2^{-5}		meters
ω	32*	2^{-31}		semi-circles
OMEGADO	24*	2^{-43}		semi-circles/sec
T	14*	2^{-43}		semi-circles/sec
IDOT				

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB.

** See Figures 10-1 and 10-2 for complete bit allocation in Message Types 1 and 2.

*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

Table 10-IV. Elements of Coordinate Systems (sheet 1 of 3)	
$\mu = 3.986005 \times 10^{14}$ meters^3/sec^2	WGS 84 value of the earth's universal gravitational parameter for GPS users
$\dot{\Omega}_e = 7.2921151467 \times 10^{-5}$ rad/sec	WGS 84 value of the earth's rotation rate
$A = \left(\sqrt{A}\right)^2$	Semi-major axis
$N_0 = \sqrt{\frac{m}{A^3}}$	Computed mean motion (rad/sec)
$T_k = t - t_{oe}$*	Time from ephemeris reference epoch
$N = n_0 + \Delta n$	Corrected mean motion
$M_k = M_0 + nt_k$	Mean anomaly

* t is GPS system time at time of transmission, i.e., GPS time corrected for transit time (range/speed of light). Furthermore, t_k is the actual total time difference between the time t and the epoch time t_{oe}, and must account for beginning or end of week crossovers. That is, if t_k is greater than 302,400 seconds, subtract 604,800 seconds from t_k. If t_k is less than -302,400 seconds, add 604,800 seconds to t_k.

Table 10-IV. Elements of Coordinate Systems (sheet 2 of 3)		
$M_k = E_k - e \sin E_k$		Kepler's equation for eccentric anomaly (may be solved by iteration)(radians)
$v_k = \tan^{-1}\left\{\dfrac{\sin v_k}{\cos v_k}\right\}$		True anomaly
$= \tan^{-1}\left\{\dfrac{\sqrt{1-e^2}\sin E_k / (1-e\cos E_k)}{(\cos E_k - e)/(1-e\cos E_k)}\right\}$		
$E_k = \cos^{-1}\left\{\dfrac{e+\cos v_k}{1+e\cos v_k}\right\}$		Eccentric anomaly
$\Phi_k = v_k + \omega$		Argument of latitude
$\delta u_k = C_{us} \sin 2\Phi_k + C_{uc} \cos 2\Phi_k$	Argument of latitude correction	Second Harmonic
$\delta r_k = C_{rs} \sin 2\Phi_k + C_{rc} \cos 2\Phi_k$	Radius correction	Second Harmonic
$\delta i_k = C_{is} \sin 2\Phi_k + C_{ic} \cos 2\Phi_k$	Inclination correction	Second Harmonic
$u_k = \Phi_k + \delta u_k$		Corrected argument of latitude
$r_k = A(1-e\cos E_k) + \delta r_k$		Corrected radius
$i_k = i_0 + \delta i_k + (\mathrm{IDOT})\, t_k$		Corrected inclination

Table 10-IV. Elements of Coordinate Systems (sheet 3 of 3)	
$X_k' = r_k \cos u_k$ $Y_k' = r_k \sin u_k$	Positions in orbital
$\Omega_k = \Omega_0 + (\dot{\Omega} - \dot{\Omega}_e)\, t_k - \dot{\Omega}_e\, t_{oe}$ node.	Corrected longitude of ascending
$X_k = x_k' \cos \Omega_k - y_k' \cos i_k \sin \Omega_k$ $Y_k = x_k' \sin \Omega_k + y_k' \cos i_k \cos \Omega_k$ $Z_k = y_k' \sin i_k$	Earth-fixed

10.3.3.2.3.2 Parameter Sensitivity

The sensitivity of the SV's antenna phase center position to small perturbations in most ephemeris parameters is extreme. The sensitivity of position to the parameters $(A)^{1/2}$, C_{rc} and C_{rs} is about one meter/meter. The sensitivity of position to the angular parameters is on the order of 10^8 meters/semicircle, and to the angular rate parameters is on the order of 10^{12} meters/semicircle/second. Because of this extreme sensitivity to angular perturbations, the value of π used in the curve fit is given here. π is a mathematical constant, the ratio of a circle's circumference to its diameter. Here π is taken as

$$\pi = 3.1415926535898.$$

10.3.3.2.3.3 Coordinate Systems

10.3.3.2.3.3.1 ECEF Coordinate System

The equations given in Table 10-IV provide the SV's antenna phase center position in the WGS 84 ECEF coordinate system defined as follows:

Origin*	=	Earth's center of mass
Z-Axis**	=	The direction of the IERS (International Earth Rotation Service) Reference Pole (IRP)
X-Axis	=	Intersection of the IERS Reference Meridian (IRM) and the plane passing through the origin and normal to the Z-Axis
Y-Axis	=	Completes a right-handed, Earth-Centered-Earth-Fixed orthogonal coordinate system

* Geometric center of the WGS 84 Ellipsoid
** Rotational axis of the WGS 84 Ellipsoid

10.3.3.2.3.3.2 Earth-Centered Inertial (ECI) Coordinate System

In an ECI coordinate system, GPS signals propagate in straight lines at the constant speed c* (reference paragraph 10.3.4.3). A stable ECI coordinate system of convenience may be defined as being coincident with the ECEF coordinate system at a given time t_0. The x, y, z coordinates in the ECEF coordinate system at some other time t can be transformed to the x', y', z' coordinates in the selected ECI coordinate system of convenience by the simple** rotation:

$$
\begin{aligned}
x' &= x\cos(\theta) - y\sin(\theta) \\
y' &= x\sin(\theta) + y\cos(\theta) \\
z' &= z
\end{aligned}
$$

where

$$\theta = \dot{\Omega}_e\,(t - t_0)$$

* The propagation speed c is constant only in a vacuum. The gravitational potential also has a small effect on the propagation speed, but may be neglected by most users.

** Neglecting effects due to polar motion, nutation and precession which may be neglected by most users for small values of $(t - t_0)$.

10.3.3.2.3.4 Geometric Range

The user shall account for the geometric range (D) from satellite to receiver in an ECI coordinate system. D may be expressed as

$$D = \left| \vec{r}(t_R) - \vec{R}(t_T) \right|$$

where

t_T and t_R are the GPS system times of transmission and reception, respectively,

and where

$\vec{R}(t_T)$ = position vector of the GPS satellite in the selected ECI coordinate system at time t_T, and

$\vec{r}(t_R)$ = position vector of the receiver in the selected ECI coordinate system at time t_R.

10.3.3.3 Message Type 3 Parameters

The contents of Message Type 3 are defined below, followed by material pertinent to the use of the data.

10.3.3.3.1 Message Type 3 Parameter Content

Message Type 3 contains UTC and ionospheric parameters and other data.

10.3.3.3.1.1 Universal Coordinated Time (UTC) Parameters

Message Type 3 contains the parameters related to correlating UTC time with L5 GPS time. The bit length, scale factors, ranges, and units of these parameters are given in Table 10-V. The related algorithms are described in paragraph 10.3.3.3.2.1. Change parameters to relate L5 to UTC, or add parameters to relate L5 GPS time to GPS time.

The UTC parameters will be updated by the CS at least once every six days while the CS is able to upload the SVs. If the CS is unable to upload the SVs, the accuracy of the UTC parameters transmitted by the SVs will degrade over time.

10.3.3.3.1.2 Ionospheric Data

The ionospheric parameters which allow the “L1 only”, “L2 only” or “L5 only” user to utilize the ionospheric model (reference paragraph 10.3.3.3.2.2) for computation of the ionospheric delay are contained in Message Type 3. The bit lengths, scale factors, ranges, and units of these parameters are given in Table 10-VI.

The ionospheric data will be updated by the CS at least once every six days while the CS is able to upload the SVs. If the CS is unable to upload the SVs, the ionospheric data transmitted by the SVs may not be accurate.

10.3.3.3.1.3 SV Health (L1/L2)

The six-bit health indication in bits 43 through 48 refers to the transmitting SV for the L1 and L2 signals. The MSB indicates a summary of the health of the NAV data, where

0 = all NAV data are OK,
1 = some or all NAV data are bad.

The five LSBs indicate the health of the L1 and L2 signal components in accordance with the codes given in paragraph 10.3.3.4.1.3. The health indication is given relative to the "as designed" capabilities of each SV (as designated by the configuration code – see paragraph 10.3.3.4.1.5). Accordingly, any SV that does not have a certain capability will be indicated as “healthy” if the lack of this capability is inherent in its design or if it has been configured into a mode that is normal from a user standpoint and does not require that capability.

Additional SV health data are given in Message Type 4, the Almanac message. The data given in Message Type 3 may differ from that shown in Message Type 4 on other SVs since the latter may be updated at a different time.

10.3.3.3.1.4 Code(s) on L2 Channel

Bits 41 and 42 of Message Type 3 indicate which code(s) is (are) commanded ON for the L2 channel, as follows:

00	=	Both P and C/A code ON,
01	=	P code ON,
10	=	C/A code ON.

Table 10-V. UTC Parameters

Parameter	No. of Bits**	Scale Factor (LSB)	Effective Range***	Units
A_0	32*	2^{-30}		seconds
δA_{05}	8*	2^{-30}		seconds
A_1	24*	2^{-50}		sec/sec
δA_{15}	8*	2^{-50}		sec/sec
Δt_{LS}	8*	1		seconds
t_{ot}	8	2^{12}	602,112	seconds
WN_t	8	1		weeks
WN_{LSF}	8	1		weeks
DN	8****	1	7	days
Δt_{LSF}	8*	1		seconds

* Parameters so indic ated are two's complement with the sign bit (+ or -) occupying the MSB.

** See Figure 10-3 for complete bit allocation in Message Type 3.

*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

**** Right justified.

Parameter	No. of Bits**	Scale Factor (LSB)	Effective Range***	Units
Table 10-VI. Ionospheric Parameters				
α_0	8*	2^{-30}		Seconds
α_1	8*	2^{-27}		sec/semi-circle
α_2	8*	2^{-24}		sec/(semi-circle)^2
α_3	8*	2^{-24}		sec/(semi-circle)^3
β_0	8*	2^{11}		seconds
β_1	8*	2^{14}		sec/semi-circle
β_2	8*	2^{16}		sec/(semi-circle)^2
β_3	8*	2^{16}		sec/(semi-circle)^3

* Parameters so indicated are two's complement with the sign bit (+ or -) occupying the MSB.

** See Figure 10-3 for complete bit allocation in Message Type 3.

*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

10.3.3.3.2 Algorithms Related to Message Type 3 Data

The following algorithms will apply when interpreting Universal Coordinated Time and Ionospheric Model data in the NAV message.

10.3.3.3.2.1 Universal Coordinated Time (UTC)

Message Type 3 includes: (1) the parameters needed to relate GPS time to UTC, and (2) notice to the user regarding the scheduled future or recent past (relative to NAV message upload) value of the delta time due to leap seconds (Δt_{LSF}), together with the week number (WN_{LSF}) and the day number (DN) at the end of which the leap second becomes effective. "Day one" is the first day relative to the end/start of week and the WN_{LSF} value consists of eight bits which are a Modulo 256 binary representation of the GPS week number (see paragraph 4.2.4) to which the DN is referenced. The user must account for the truncated nature of this parameter as well as truncation of WN, WN_t, and WN_{LSF} due to rollover of the week number (see paragraph 3.3.4(b)). The CS will manage these parameters such that the absolute value of the difference between the untruncated WN and WN_{LSF} values does not exceed 127.

Depending upon the relationship of the effectivity date to the user's current GPS time, the following three different UTC/GPS-time relationships exist:

a. Whenever the effectivity time indicated by the WN_{LSF} and the DN values is not in the past (relative to the user's present time), <u>and</u> the user's present time does not fall in the time span which starts at DN + 3/4 and ends at DN + 5/4, the UTC/GPS-time relationship is given by

$$t_{UTC} = (t_E - \Delta t_{UTC}) \text{ [Modulo 86400 seconds]}$$

where t_{UTC} is in seconds and

Δt_{UTC} = $\Delta t_{LS} + A_0 + \delta A_{05} + (A_1 + \delta A_{15})(t_E - t_{ot} + 604800\,(WN - WN_t))$, seconds;

t_E = GPS L5 time as estimated by the user on the basis of correcting t_{SV} for factors described in paragraph 10.3.3.1.3 as well as for ionospheric and SA (dither) effects;

Δt_{LS} = delta time due to leap seconds;

A_0 and A_1 = constant and first order terms of polynomial;

t_{ot} = reference time for UTC data (reference 10.3.4.5);

WN = current week number (derived from Message Type 3);

WN_t = UTC reference week number.

The estimated GPS L5 time (t_E) is in seconds relative to end/start of week. The reference time for UTC data (t_{ot}) is referenced to the start of that week whose number (WN_t) is given in Message Type 3. The WN_t value consists of eight bits which are a Modulo 256 binary representation of the GPS week number (see paragraph) 4.2.4) to which the t_{ot} is referenced. The user must account for the truncated nature of this parameter as well as truncation of WN, WN_t, and WN_{LSF} due to rollover of the week number (see paragraph 3.3.4(b)). The CS will manage these parameters such that the absolute value of the difference between the untruncated WN and WN_t values does not exceed 127.

b. Whenever the user's current time falls within the time span of DN + 3/4 to DN + 5/4, proper accommodation of the leap second event with a possible week number transition is provided by the following expression for UTC:

$$t_{UTC} = W[\text{Modulo } (86400 + \Delta t_{LSF} - \Delta t_{LS})], \text{ seconds;}$$

where

$$W = (t_E - \Delta t_{UTC} - 43200)[\text{Modulo } 86400] + 43200, \text{ seconds;}$$

and the definition of Δt_{UTC} (as given in 10.3.3.3.2.1a above) applies throughout the transition period. Note that when a leap second is added, unconventional time values of the form 23:59:60.xxx are encountered. Some user equipment may be designed to approximate UTC by decrementing the running count of time within several seconds after the event, thereby promptly returning to a proper time indication. Whenever a leap second event is encountered, the user equipment must consistently implement carries or borrows into any year/week/day counts.

c. Whenever the effectivity time of the leap second event, as indicated by the WN_{LSF} and DN values, is in the "past" (relative to the user's current time), the relationship previously given for t_{UTC} in 10.3.3.3.2.1a above is valid except that the value of Δt_{LSF} is substituted for Δt_{LS}. The CS will coordinate the update of UTC parameters at a future upload so as to maintain a proper continuity of the t_{UTC} time scale.

10.3.3.3.2.2 Ionospheric Model

The "two frequency" user shall correct the time received from the SV for ionospheric effect by utilizing the time delay differential between a subset of L1, L2, and L5. The "one frequency" user, however, may use the model given in Figure 10-7 to make this correction. It is estimated that the use of this model will provide at least a 50 percent reduction in the single-frequency user's RMS error due to ionospheric propagation effects. During extended operations, if the CS is unable to upload the SVs, the use of this model will yield unpredictable results.

The ionospheric correction model is given by

$$T_{iono} = \begin{cases} F * \left[5.0*10^{-9} + (AMP)\left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right)\right], & |x| < 1.57 \\ F * \left(5.0*10^{-9}\right), & |x| \geq 1.57 \end{cases} \quad \text{(sec)}$$

where

T_{iono} is referred to the L1 frequency; if the user is operating on the L2 or L5 frequency, the correction term must be multiplied by γ_{12} or γ_{15} (reference paragraph 10.3.3.1.3.2 or 10.3.3.1.3.5), depending upon the frequency used,

$$AMP = \begin{cases} \sum_{n=0}^{3} \boldsymbol{a}_n \boldsymbol{f}_m^n, & AMP \geq 0 \\ \text{if } AMP < 0, & AMP = 0 \end{cases} \quad \text{(sec)}$$

$$x = \frac{2\boldsymbol{p}(t - 50400)}{PER}, \text{ (radians)}$$

$$PER = \begin{cases} \sum_{n=0}^{3} \boldsymbol{b}_n \boldsymbol{f}_m^n, & PER \geq 72{,}000 \\ \text{if } PER < 72{,}000, & PER = 72{,}000 \end{cases} \quad \text{(sec)}$$

$F = 1.0 + 16.0\,[0.53 - E]^3$

and α_n and β_n are the satellite transmitted data words with n = 0, 1, 2, and 3.

<u>Figure 10-7.</u> Ionospheric Model (Sheet 1 of 3)

Other equations that must be solved are

$$\phi_m = \phi_i + 0.064\cos(\lambda_i - 1.617) \qquad \text{(semi-circles)}$$

$$l_i = l_u + \frac{y\ \sin A}{\cos f_i} \text{ (semi-circles)}$$

$$f_i = \left\{ \begin{array}{l} f_u + y\cos A(\text{semi} - \text{circles}),\ |f_i| \le 0.416 \\ \quad \text{if } f_i > +0.416, \text{ then } f_i = +0.416 \\ \quad \text{if } f_i < -0.416, \text{ then } f_i = -0.416 \end{array} \right\} \quad \text{(semi-circles)}$$

$$y = \frac{0.0137}{E + 0.11} - 0.022 \qquad \text{(semi-circles)}$$

$$t = 4.32 * 10^4 \lambda_i + \text{GPS time (sec)}$$

where

$0 \le t < 86400$: therefore, if $t \ge 86400$ seconds, subtract 86400 seconds;
if $t < 0$ seconds, add 86400 seconds.

Figure 10-7. Ionospheric Model (Sheet 2 of 3)

The terms used in computation of ionospheric delay are as follows:

• Satellite Transmitted Terms

α_n	the coefficients of a cubic equation representing the amplitude of the vertical delay (4 coefficients – 8 bits each)
β_n	the coefficients of a cubic equation representing the period of the model (4 coefficients – 8 bits each)

• Receiver Generated Terms

E	elevation angle between the user and satellite (semi-circles)
A	azimuth angle between the user and satellite, measured clockwise positive from the true North (semi-circles)
ϕ_u	user geodetic latitude (semi-circles) WGS-84
λ_u	user geodetic longitude (semi-circles) WGS-84
GPS time	receiver computed system time

• Computed Terms

x	phase (radians)
F	obliquity factor (dimensionless)
t	local time (sec)
ϕ_m	geomagnetic latitude of the earth projection of the ionospheric intersection point (mean ionospheric height assumed 350 km) (semi-circles)
λ_i	geodetic longitude of the earth projection of the ionospheric intersection point (semi-circles)
ϕ_i	geodetic latitude of the earth projection of the ionospheric intersection point (semi-circles)
ψ	earth's central angle between the user position and the earth projection of ionospheric intersection point (semi-circles)

Figure 10-7. Ionospheric Model (Sheet 3 of 3)

10.3.3.4 Message Type 4 Almanac Parameters

The contents of Message Type 4 are defined below, followed by material pertinent to the use of the data.

10.3.3.4.1 Message Type 4 Almanac Parameter Content

Message Type 4 contains almanac data.

10.3.3.4.1.1 Data ID and SV ID

The two bits of the data ID which defines the applicable GPS NAV data structure. Data ID one (denoted by binary code 00) was utilized during Phase I of the GPS program and is no longer in use; data ID two (denoted by binary code 01) is used on the L1 and L2 C/A and P(Y) code signals. Data ID three (denoted by binary 10) is used on this L5 signal. Future data IDs will be defined as necessary.

10.3.3.4.1.2 Almanac Data

Message Type 4 contains the almanac data and SV health words for up to 37 SVs (the health words are discussed in paragraphs 10.3.3.1.1.3 and 10.3.3.3.1.3). The almanac data are a reduced-precision subset of the clock and ephemeris parameters. The number of bits, the scale factor (LSB), the range, and the units of the almanac parameters are given in Table 10-VII. The algorithms and other material related to the use of the almanac data are given in paragraph 10.3.3.4.2.

The almanac parameters will be updated by the CS at least once every 6 days while the CS is able to upload the SVs. If the CS is unable to upload the SVs, the accuracy of the almanac parameters transmitted by the SVs will degrade over time.

10.3.3.4.1.3 SV Health (L1 and L2)

Message Type 4 contains two types of SV health data for the SV indicated with by the PRN_a parameter: (a) L1 and L2 health, and (b) L5 health. The L5 health data is described in paragraph 10.3.3.4.1.4

The three MSBs of the eight-bit L1/L2 health words in Message Type 4 indicate health of the NAV data in accordance with the code given in Table 10-VIII. The six-bit L1/L2 health words in Message Type 3 provide a one-bit summary of the NAV data's health status in the MSB position in accordance with paragraph 10.3.3.3.1.3. The five LSBs of both the eight-bit and the six-bit words provide the health status of the SV's signal components in accordance with the code given in Table 10-IX.

The data given in Message Type 3 of the other SVs may differ from that shown in Message Type 4 since the latter may be updated at a different time.

The predicted health data will be updated at the time of upload when a new almanac has been built by the CS. The transmitted health data may not correspond to the actual health of the transmitting SV or other SVs in the constellation.

10.3.3.4.1.4 SV Health (L5)

The three MSBs of the seven-bit L5 health words in Message Type 4 indicate health of the NAV data in accordance with the code given in Table 10-X. The five-bit L5 health words in Message Type 3 provide a one-bit summary of the NAV data's health status in the MSB position in accordance with paragraph 10.3.3.3.1.3. The four LSBs of both the seven-bit and the five-bit words provide the health status of the SV's signal components in accordance with the code given in Table 10-XI.

The data given in Message Type 3 of the other SVs may differ from that shown in Message Type 4 since the latter may be updated at a different time.

The predicted health data will be updated at the time of upload when a new almanac has been built by the CS. The transmitted health data may not correspond to the actual health of the transmitting SV or other SVs in the constellation.

10.3.3.4.1.5 Anti-Spoof (A-S) Flags and SV Configurations

Message Type 4 contains a four-bit-long term for each of up to 32 SVs to indicate the A-S status (of the L1 and L2 signals) and the configuration code of each SV. The MSB of each four-bit term is the A-S flag with a "1" indicating that A-S is ON. The three LSBs indicate the configuration of each SV using the following code:

Code	SV Configuration
001	"Block II/IIA/IIR" SV (A-S capability, plus flags for A-S and "alert" in HOW; memory capacity as described in paragraph 10.3.2).

Additional codes will be assigned in the future, should the need arise.

These four-bit terms occupy bits 225 to 228 of Message Type 4.

Since the anti-spoof information is updated by the CS at the time of upload, the anti-spoof data may not correspond to the actual anti-spoof status of the transmitting SV or other SVs in the constellation.

10.3.3.4.1.6 Almanac Reference Week

Bits 47 through 56 of Message Type 4 indicate the number of the week (WN_a) to which the almanac reference time (t_{oa}) is referenced (see paragraphs 10.3.3.4.1.2 and 10.3.3.4.2.2). The WN_a term consists of eight bits which are a Modulo 256 binary representation of the GPS week number (see paragraph 4.2.4) to which the t_{oa} is referenced. Bits 73 through 80 of Message Type 4 contain the value of t_{oa}, which is referenced to this WN_a.

Table 10-VII. Almanac Parameters

Parameter	No. of Bits**	Scale Factor (LSB)	Effective Range***	Units
E	16	2^{-21}		dimensionless
t_{oa}	8	2^{12}	602,112	seconds
δ_i****	16*	2^{-19}		semi-circles
OMEGADOT	16*	2^{-38}		semi-circles/sec
$(A)^{1/2}$	24	2^{-11}		$\text{meters}^{1/2}$
$(\text{OMEGA})_0$	24*	2^{-23}		semi-circles
ω	24*	2^{-23}		semi-circles
M_0	24*	2^{-23}		semi-circles
a_{f0}5	11*	2^{-20}		seconds
a_{f1}5	11*	2^{-38}		sec/sec

* Parameters so indicated are two's complement with the sign bit (+ or -) occupying the MSB.

** See Figure 10-4 for complete bit allocation in Message Type 4.

*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

**** Relative to i_0 = 0.30 semi-circles.

Table 10-VIII. L1/L2 NAV Data Health Indications

Bit Position in 8-Bit L1/L2 Health Word			Indication
1	2	3	
0	0	0	ALL DATA OK
0	0	1	PARITY FAILURE – some or all parity bad
0	1	0	TLM/HOW FORMAT PROBLEM – any departure from standard format (e.g., preamble misplaced and/or incorrect, etc.), except for incorrect Z-count, as reported in HOW
0	1	1	Z-COUNT IN HOW BAD – any problem with Z-count value not reflecting actual code phase
1	0	0	Subframes 1, 2, 3 – one or more elements in words three through ten of one or more subframes are bad
1	0	1	Subframes 4, 5 – one or more elements in words three through ten of one or more subframes are bad
1	1	0	ALL UPLOADED DATA BAD – one or more of the uploaded elements in words three through ten of any one (or more) subframes are bad
1	1	1	ALL DATA BAD – TLM word and/or HOW and one or more elements in any one (or more) subframes are bad

<u>Table 10-IX</u>. Codes for Health of SV L1/L2 Signal Components

MSB LSB	Definition
0 0 0 0 0	All Signals OK
0 0 0 0 1	All Signals Weak*
0 0 0 1 0	All Signals Dead
0 0 0 1 1	All Signals Have No Data Modulation
0 0 1 0 0	L1 P Signal Weak
0 0 1 0 1	L1 P Signal Dead
0 0 1 1 0	L1 P Signal Has No Data Modulation
0 0 1 1 1	L2 P Signal Weak
0 1 0 0 0	L2 P Signal Dead
0 1 0 0 1	L2 P Signal Has No Data Modulation
0 1 0 1 0	L1 C Signal Weak
0 1 0 1 1	L1 C Signal Dead
0 1 1 0 0	L1 C Signal Has No Data Modulation
0 1 1 0 1	L2 C Signal Weak
0 1 1 1 0	L2 C Signal Dead
0 1 1 1 1	L2 C Signal Has No Data Modulation
1 0 0 0 0	L1 & L2 P Signal Weak
1 0 0 0 1	L1 & L2 P Signal Dead
1 0 0 1 0	L1 & L2 P Signal Has No Data Modulation
1 0 0 1 1	L1 & L2 C Signal Weak
1 0 1 0 0	L1 & L2 C Signal Dead
1 0 1 0 1	L1 & L2 C Signal Has No Data Modulation
1 0 1 1 0	L1 Signal Weak*
1 0 1 1 1	L1 Signal Dead
1 1 0 0 0	L1 Signal Has No Data Modulation
1 1 0 0 1	L2 Signal Weak*
1 1 0 1 0	L2 Signal Dead
1 1 0 1 1	L2 Signal Has No Data Modulation
1 1 1 0 0	SV <u>Is</u> Temporarily Out (Do not use this SV during current pass**)
1 1 1 0 1	SV <u>Will Be</u> Temporarily Out (Use with caution**)
1 1 1 1 0	Spare
1 1 1 1 1	More Than One Combination Would Be Required To Describe Anomalies (Except those marked by **)

* 3 to 6 dB below specified power level due to reduced power output, excess phase noise, SV attitude, etc.

Table 10-X. L5 NAV Data Health Indications			
Bit Position in 7-Bit L5 Health Word			Indication
1	2	3	
0	0	0	ALL DATA OK
0	0	1	PARITY FAILURE – some or all parity bad
0	1	0	TLM/HOW FORMAT PROBLEM – any departure from standard format (e.g., preamble misplaced and/or incorrect, etc.), except for incorrect Z-count, as reported in HOW
0	1	1	Z-COUNT IN HOW BAD – any problem with Z-count value not reflecting actual code phase
1	0	0	Message Types 1 and 2 – one or more elements in one or more of the messages are bad
1	0	1	Message Types 3 and 4 – one or more elements in one or more of the messages are bad
1	1	0	ALL UPLOADED DATA BAD – one or more of the uploaded elements in any one (or more) of the messages are bad
1	1	1	ALL DATA BAD – one or more elements in any one (or more) of the messages are bad

Table 10-XI. Codes for Health of SV L5 Signal Components

MSB LSB	Definition
0 0 0 0	All Signals (I & Q) OK
0 0 0 1	All Signals (I & Q) Weak*
0 0 1 0	All Signals (I & Q) Dead
0 0 1 1	I Signal Has No Data Modulation
0 1 0 0	I Signal Is Weak
0 1 0 1	I Signal Is Dead
0 1 1 0	Q Signal Is Weak
0 1 1 1	Q Signal Is Dead
1 0 0 0	L5 Specific Data Is Bad
1 0 0 1	L5 Parity Is Bad
1 0 1 0	Spare
1 0 1 1	Spare
1 1 0 0	Spare
1 1 0 1	Spare
1 1 1 0	Spare
1 1 1 1	More Than One Combination Would Be Required To Describe Anomalies

* 3 to 6 dB below specified power level due to reduced power output, excess phase noise, SV attitude, etc.

10.3.3.4.2 Algorithms Related to Message Type 4 Data

The following algorithms apply when interpreting Almanac data in the NAV message.

10.3.3.4.2.1 Almanac

The almanac is a subset of the clock and ephemeris data, with reduced precision. The user algorithm is essentially the same as the user algorithm used for computing the precise ephemeris from the Message Type 1 and 2 parameters (see Table 10-IV). The almanac content for one SV is given in Table 10-VII. A close inspection of Table 10-VII will reveal that a nominal inclination angle of 0.30 semicircles is implicit and that the parameter δ_i (correction to inclination) is transmitted, as opposed to the value computed by the user. All other parameters appearing in the equations of Table 10-IV, but not included in the content of the almanac, are set to zero for SV position determination. In these respects, the application of the Table 10-IV equations differs between the almanac and the ephemeris computations.

The user is cautioned that the sensitivity to small perturbations in the parameters is even greater for the almanac than for the ephemeris, with the sensitivity of the angular rate terms over the interval of applicability on the order of 10^{14} meters/(semicircle/second). An indication of the URE provided by a given almanac during each of the operational intervals is as follows:

Operational Interval	Almanac Ephemeris URE (estimated by analysis) 1 sigma (meters)
Normal	900*
Short-term Extended	900 - 3,600*
Long-term Extended	3600 - 300,000*

* URE values generally tend to degrade quadratically over time. Larger errors may be encountered during eclipse seasons and whenever a propulsive event has occurred.

10.3.3.4.2.2 Almanac Reference Time

Normal and Short-term Extended Operations. The almanac reference time, t_{oa}, is some multiple of 2^{12} seconds occurring approximately 70 hours after the first valid transmission time for this almanac data set (reference 10.3.4.5). The almanac is updated often enough to ensure that GPS time, t, differs from t_{oa} by less than 3.5 days during the transmission period. The time from epoch t_k shall be computed as described in Table 10-IV, except that t_{oe} shall be replaced with t_{oa}.

Long-term Extended Operations. During long-term extended operations or if the user wishes to extend the use time of the almanac beyond the time span that it is being transmitted, one must account for crossovers into time spans where these computations of t_k are not valid. This may be accomplished without time ambiguity by recognizing that the almanac reference time (t_{oa}) is referenced to the almanac reference week (WN_a), both of which are given in Message Type 4 (see paragraph 10.3.3.4.1.6).

10.3.3.4.2.3 Almanac Time Parameters

The almanac time parameters consist of an 11-bit constant term (a_{f0}) and an 11-bit first order term (a_{f1}). The applicable first order polynomial, which provides time to within 2 microseconds of GPS time (t) during the interval of applicability, is given by

$$t = t_{sv} - \Delta t_{sv}$$

where

t = GPS system time (seconds),
t_{sv} = effective SV PRN code phase time at message transmission time (seconds),
Δt_{sv} = SV PRN code phase time offset (seconds).

The SV PRN code phase offset is given by

$$\Delta t_{sv} = a_{f05} + a_{f15}\, t_k$$

where the computation of t_k is described in paragraph 10.3.3.4.2.2, and the polynomial coefficients a_{f05} and a_{f15} are given in the almanac. Since the periodic relativistic effect is less than 25 meters, it need not be included in the time scale used for almanac evaluation. Over the span of applicability, it is expected that the almanac time parameters will provide a statistical URE component of less than 135 meters, one sigma. This is partially due to the fact that the error caused by the truncation of a_{f0} and a_{f1} may be as large as 150 meters plus 50 meters/day relative to the t_{oa} reference time.

Note: During extended operations (short-term and long-term) the almanac time parameter may not provide the specified time accuracy or URE component.

10.3.3.5 Message Type 5

Message Type 5 is reserved for special messages with the specific contents at the discretion of the Operating Command. It can accommodate the transmission of 29 eight-bit ASCII characters. The requisite 232 bits occupy bits 41 through 272 of Message Type 5. The eight-bit ASCII characters shall be limited to the following set:

Alphanumeric Character	ASCII Character	Code (Octal)
A - Z	A - Z	101 - 132
0 - 9	0 - 9	060 - 071
+	+	053
-	-	055
. (Decimal point)	.	056
' (Minute mark)	'	047
° (Degree sign)	°	370
/	/	057
Blank	Space	040
:	:	072
" (Second mark)	"	042

10.3.4 Timing Relationships

The following conventions shall apply.

10.3.4.1 Paging and Cutovers

Paging of messages is completely arbitrary, but sequenced to provide optimum user performance.

10.3.4.2 SV Time vs. GPS Time

In controlling the SVs and uploading of data, the CS shall allow for the following timing relationships:

a. Each SV operates on its own SV time;
b. All time-related data (TOW) in the messages shall be in SV-time;
c. All other data in the NAV message shall be relative to GPS time;
d. The acts of transmitting the NAV messages shall be executed by the SV on SV time.

10.3.4.3 Speed of Light

The speed of light used by the CS for generating the data described in the above paragraphs is

$$c = 2.99792458 \times 10^{8} \text{ meters per second}$$

which is the official WGS-84 speed of light. The user shall use the same value for the speed of light in all computations.

10.3.4.4 Data Sets

The IODE is an 10 bit number equal to the 10 bit IODC of the same data set. The following rule govern the transmission of IODC and IODE values in different data sets: The transmitted IODC and IODE will be different from any value transmitted by the SV during the preceding seven days. The range of IODC and IODE will be as given in Table 10-XII.

Cutovers to new data sets will occur only on hour boundaries except for the first data set of a new upload. The first data set may be cut-in (reference paragraph 10.3.4.1) at any time during the hour and therefore may be transmitted by the SV for less than one hour. During short-term operations, cutover to 4-hour sets and subsequent cutovers to succeeding 4-hour data sets will always occur Modulo 4 hours relative to end/start of week. Cutover from 4-hour data sets to 6-hour data sets will occur Modulo 12 hours relative to end/start of week. Cutover from 12-hour data sets to 24-hour data sets will occur Modulo 24 hours relative to end/start of week. Cutover from a data set transmitted 24 hours or more occurs on a Modulo 24-hour boundary relative to end/start of week.

The start of the transmission interval for each data set corresponds to the beginning of the curve fit interval for the data set. Each data set remains valid for the duration of its curve fit interval.

Normal Operations. Message Type 1 and 2 data sets are transmitted by the SV for periods of one hour. The corresponding curve fit interval is four hours. The corresponding curve-fit interval will be four hours.

Short-term and Long-term Extended Operations. The transmission intervals and curve fit intervals with the applicable IODC/IODE ranges are given in Table 10-XII.

<u>Table 10-XII</u>. IODC/IODE Values and Data Set Lengths

Days Spanned	Transmission Interval (hours) (Note 5)	Curve Fit Interval (hours)	IODC Range (Note 1)
1	2 (Note 4)	4	(Note 2)
2-14	4	6	(Note 2)
15-16	6	8	240-247
17-20	12	14	248-255, 496 (Note 3)
21-27	24	26	497-503
28-41	48	50	504-510
42-59	72	74	511, 752-756
60-87	96	98	757-763
88-122	120	122	764-767, 1008-1010
123-182	144	146	1011-1020

<u>Notes</u>:

1. *For transmission intervals of 6 hours or greater, the IODC values shown will be transmitted in increasing order.*

2. *IODC values for blocks with 2- or 4-hour transmission intervals (at least the first 14 days after upload) shall be any numbers in the range 0 to 1023, subject to the constraints on re-transmission given in paragraph 10.3.4.4.*

3. *The ninth 12-hour data set may not be transmitted.*

4. *Some SVs will have transmission intervals of 2 hours per paragraph 10.3.4.4.*

5. *The first data set of a new upload may be cut-in at any time during the hour and therefore may be transmitted by the SV for less than an hour.*

10.3.4.5 Reference Times

Many of the parameters which describe the SV state vary with true time, and must therefore be expressed as time functions with coefficients provided by the Navigation Message so as to be evaluatable by the user equipment. These include the following parameters as functions of GPS time:

a. SV time,
b. Mean anomaly,
c. Longitude of ascending node,
d. UTC,
e. Inclination.

Each of these parameters is formulated as a polynomial in time. The specific time scale of expansion can be arbitrary. Due to the short data field lengths available in the Navigation Message format, the nominal epoch of the polynomial is chosen near the midpoint of the expansion range so that quantization error is small. This results in time epoch values which can be different for each data set. Time epochs contained in the Navigation Message and the different algorithms which utilize them are related as follows:

Epoch	Application Algorithm Reference
t_{oc}	10.3.3.1.3.1
t_{oe}	10.3.3.2.3
t_{oa}	10.3.3.4.2.2 and 10.3.3.4.2.3
t_{ot}	10.3.3.3.2.1

Table 10-XIII describes the nominal selection which will be expressed Modulo 604,800 seconds in the Navigation Message.

The coefficients of expansion are obviously dependent upon choice of epoch, and thus the epoch time and expansion coefficients must be treated as an inseparable parameter set. Note that a user applying current navigation data will normally be working with negative values of $(t-t_{oc})$ and $(t-t_{oe})$ in evaluating the expansions.

The CS will introduce small deviations from the nominal if necessary to preclude possible data set transition ambiguity when a new upload is cut over for transmission. A change from the reference time is used to indicate a change of values in the data set.

Table 10-XIII. Reference Times

Fit Interval (hours)	Transmission Interval (hours)	Hours After First Valid Transmission Time			
		t_{oc} (clock)	t_{oe} (ephemeris)	t_{oa} (almanac)	t_{ot} (UTC)
4	2*	2	2		
6	4	3	3		
8	6	4	4		
14	12	7	7		
26	24	13	13		
50	48	25	25		
74	72	37	37		
98	96	49	49		
122	120	61	61		
146	144	73	73		
144 (6 days)	144			70	70
144 (6 days)	4080			70	70

* Some SVs will have transmission intervals of 2 hours per paragraph 10.3.4.4.

10.3.5 Data Frame Parity

The data signal contains parity coding according to the following conventions.

10.3.5.1 Parity Algorithm

Twenty-four bits of CRC parity will provide protection against burst as well as random errors with a probability of undetected error $\leq 2^{-24} = 5.96 \times 10^{-8}$ for all channel bit error probabilities ≤ 0.5. The CRC word is calculated in the forward direction on a given message using a seed of 0. The sequence of 24 bits ($p_1, p_2, \ldots, p_{24}$) is generated from the sequence of information bits ($m_1, m_2, \ldots, m_{276}$) in a given message. This is done by means of a code that is generated by the polynomial

$$g(X) = \sum_{i=0}^{24} g_i X^i$$

where

g_i = 1 for i = 0,1,3,4,5,6,7,10,11,14,17,18,23,24

= 0 otherwise

This code is called CRC-24Q (Q for Qualcomm Corporation). The generator polynomial of this code is in the following form (using binary polynomial algebra):

$$g(X) = (1 + X)\,p(X)$$

where $p(X)$ is the primitive and irreducible polynomial

$$\begin{aligned} p(X) = {} & X^{23} + X^{17} + X^{13} + X^{12} \\ & + X^{11} + X^{9} + X^{8} + X^{7} + X^{5} + X^{3} + 1 \end{aligned}$$

When, by the application of binary polynomial algebra, the above $g(X)$ is divided into $m(X)X^{24}$, where the information sequence $m(X)$ is expressed as

$$m(X) = m_k + m_{k-1}X + m_{k-2}X^2 + \cdots + m_1 X^{k-1}$$

The result is a quotient and a remainder $R(X)$ of degree < 24. The bit sequence formed by this remainder represents the parity check sequence. Parity bit p_i, for any i from 1 to 24, is the coefficient of X^{24-i} in $R(X)$.

This code has the following characteristics:

a. It detects all single bit errors per code word.

b. It detects all double bit error combinations in a codeword because the generator polynomial $g(X)$ has a factor of at least three terms.

c. It detects any odd number of errors because $g(X)$ contains a factor $1+X$.

d. It detects any burst error for which the length of the burst is ≤ 24 bits.

e. It detects most large error bursts with length greater than the parity length r = 24 bits. The fraction of error bursts of length b > 24 that are undetected is:

1. $2^{-24} = 5.96 \times 10^{-8}$, if b > 25 bits

2. $2^{-23} = 1.19 \times 10^{-7}$, if b = 25 bits

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