Enhanced WWVB Broadcast Format

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1. Introduction

The WWVB broadcast of the official time of the US government has existed since 1965, at which time a modulation scheme based on amplitude modulation (AM) and pulse-width modulation (PWM) was chosen, to allow for simple implementation of a receiver. Since then, NIST has upgraded the broadcast system and modified the signal several times, making the service more accessible to the public, and resulting in the prevalence of radio-controlled clocks (RCCs). About a decade ago, a significant increase in broadcast power, as well as an increase in the modulation factor used for the amplitude-modulation, were introduced, both of which served to improve reception coverage for existing RCCs and increase their reliability. Nevertheless, it has been realized that RCCs still often encounter difficulties in reception, which depend on their geographical location, time of day, type of structure they are placed in, and sources of interference. All of these factors determine the signal-to-noise-and-interference-ratio (SNIR) that a receiver experiences at a given instance.

In order to address the reception challenges and provide the public with a much improved system, NIST has introduced an enhanced broadcast format, to which phase modulation was added, offering significantly improved performance in new RCCs that are designed according to the new broadcast format. The new broadcast format maintains the modulation of the legacy broadcast format (AM/PWM), the details of which have been made available in *NIST Special Publication 250-67* from 2005 (http://tf.nist.gov/general/pdf/1969.pdf), where additional information about the WWVB station may be found. This backward compatibility ensures that RCCs that receive the legacy time-code will continue to work as they did before, being insensitive to the phase modulation that has been added.

This document specifies the data content, physical properties and scheduling features of the phase-modulating (PM) time code that has been added to the WWVB broadcast. It is intended to allow users to correctly interpret the various components in the new PM based broadcast format. It should be noted that there are differences between the information made available through the new phase-modulating data and what has been available through the legacy AM/PWM broadcast. For example, while the time and date may be extracted from both, the leap year indication is not duplicated in the PM code, whereas the PM code contains a new field that provides advance notification for daylight-saving time (DST) transitions.

This document also describes additional modes of operation, which are being introduced at this time and were not covered in the preliminary revision of this document from 12/7/2012.

2. General Properties of the Phase Modulation (PM) Broadcast format

The signal properties of the new broadcast are designed to maintain backwards compatibility with the common envelope detector-based receivers that were designed to operate with the legacy AM/PWM WWVB broadcast format. These receivers, found in many low-cost RCCs, are typically based on a crystal filter centered at 60 kHz and having a bandwidth narrower than 10 Hz, which is followed by a non-linear envelope detection operation (rather than a coherent detector, which is based on down-conversion with a locally generated 60 kHz signal that restores the broadcast's carrier).

The PM broadcast format was designed to allow for flexibility/scalability (i.e. optimized operation at a very wide range of SNIR values), while also making provisions for additional features and extensions. It is anticipated that details of additional features will be published in future revisions of this document. These features will allow faster and more accurate synchronization, as well as further address reception at particularly low SNIR.

2.1. Definition of the Phase Modulation

The PM format is based on antipodal binary phase shift keying (BPSK), i.e. the two symbols are 180° apart. A "0" is represented by the carrier's non-modulated phase, as with the phase modulation turned off, whereas a "1" is represented by an inverted carrier. The hourly 45° phase shift that had existed in the legacy broadcast for station identification is eliminated, as station identification becomes possible based on the many unique signatures in its new PM code, which distinguish it from other broadcasts.

2.2. Physical Properties of the Modulating Baseband Signal

As can be seen in Figure 1, the baseband signal, which combines the two-level legacy AM/PWM signal and the phase (sign) inversions, may experience at least four different levels in a phase-modulated frame. These correspond to the legacy AM levels V_H and V_L, having the ratio $V_H / V_L \cong 7$, each of which may be multiplied by either a +1, representing a "0" in the BPSK modulation, or -1 for phase reversal, representing a "1" in the BPSK modulation.

The phase transition between each bit and the next one in the 1 bps (bit per second) PM frame occurs 100 ms after the AM amplitude drop that indicates the end of that second, as shown in Figure 1, illustrating an example baseband version of a transmitted symbol, where the information in the PM is shown to transition from a "0" to "1", while the transmitted AM bit is a "1". The baseband signal shown in this figure is multiplied by the 60 kHz carrier in the transmitter, thereby resulting both in variations in the carrier's amplitude and in sign reversals in it whenever the baseband signal assumes negative values.

Although the phase representing the information in each symbol is shown to be available before the amplitude in it transitions from V_H to V_L, it is recommended that receivers extract it only from the high amplitude portion of the symbol. This is not only because of the higher power there, allowing for more robust phase demodulation, but also because the low amplitude portion may be used in the future for additional (higher rate) phase modulation.

Figures 2 through 5 illustrate the modulated carrier for all of four combinations of 0/1 bit values for the legacy and the PM frames. For visual clarity, the carrier frequency in these figures was reduced from 60 kHz to 30 Hz, and band-limiting pulse-shaping filtering, which softens the transitions, has been disregarded.

Figure 6 illustrates an example of the modulated carrier for three consecutive bits representing M 0 1 for the legacy AM signal (M = marker) and, simultaneously, 0 1 0 in the phase modulated data (following a 0 bit). The combined modulating baseband signal, which represents both the information represented in the legacy AM signal and the additional information incorporated in the phase, is shown by a dashed red line. Negative values, resulting in carrier inversion, represent a "1" in the PM data.

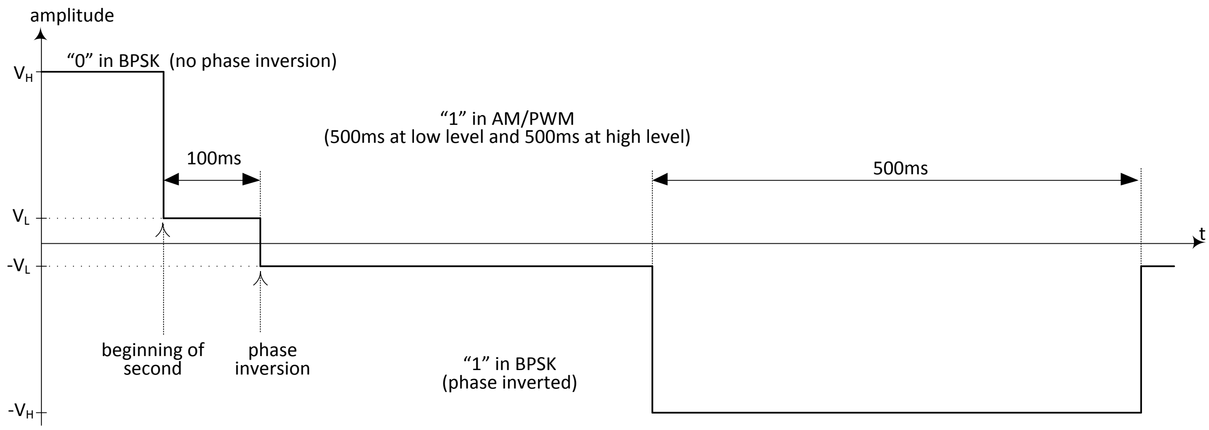

Figure 1 – The baseband signal when a “1” is transmitted both in the legacy format and in the PM

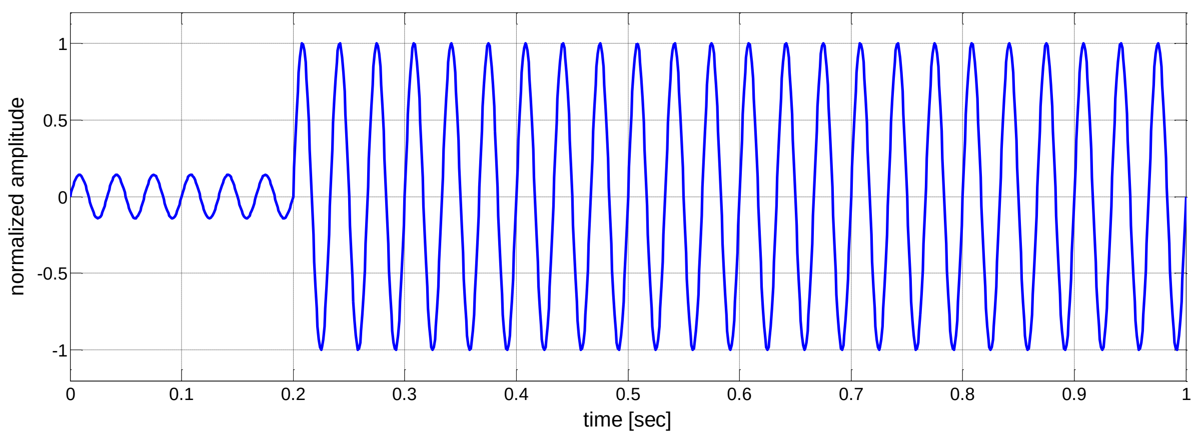

Figure 2 – The modulated carrier for a “0” both in the legacy format and in the PM

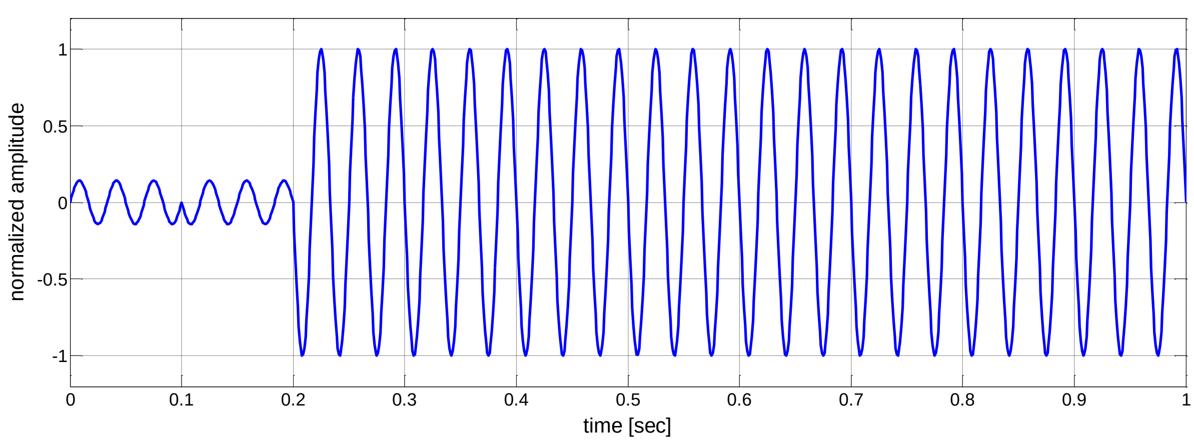

Figure 3 – The modulated carrier for a “0” in the legacy format and a “1” in the PM (following a “0”)

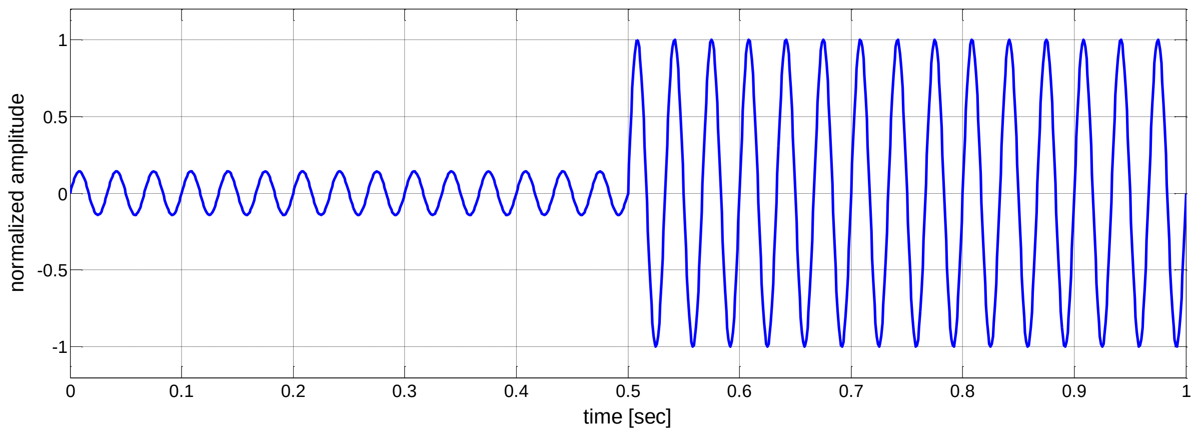

Figure 4 – The modulated carrier for a “1” in the legacy format and a “0” in the PM (following a “0”)

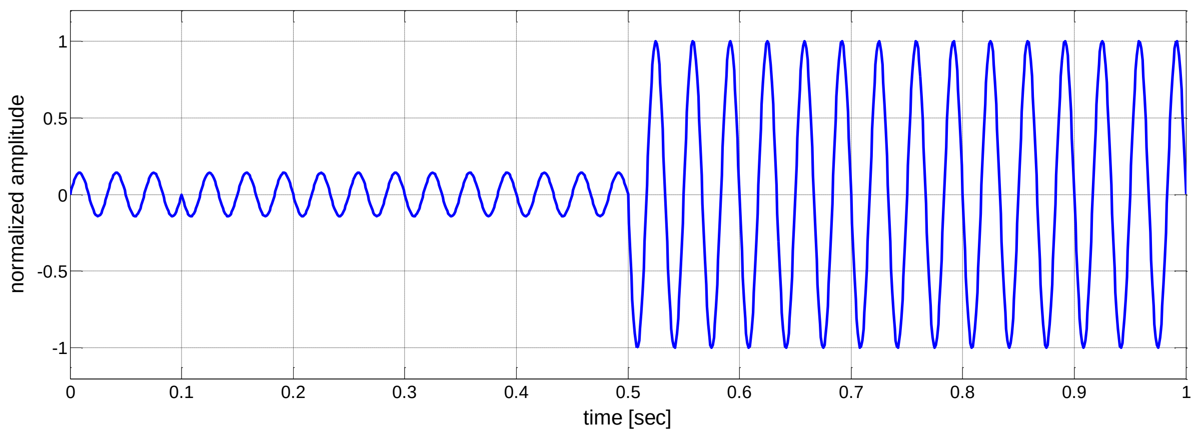

Figure 5 – The modulated carrier for a “1” both in the legacy format and in the PM (following a “0”)

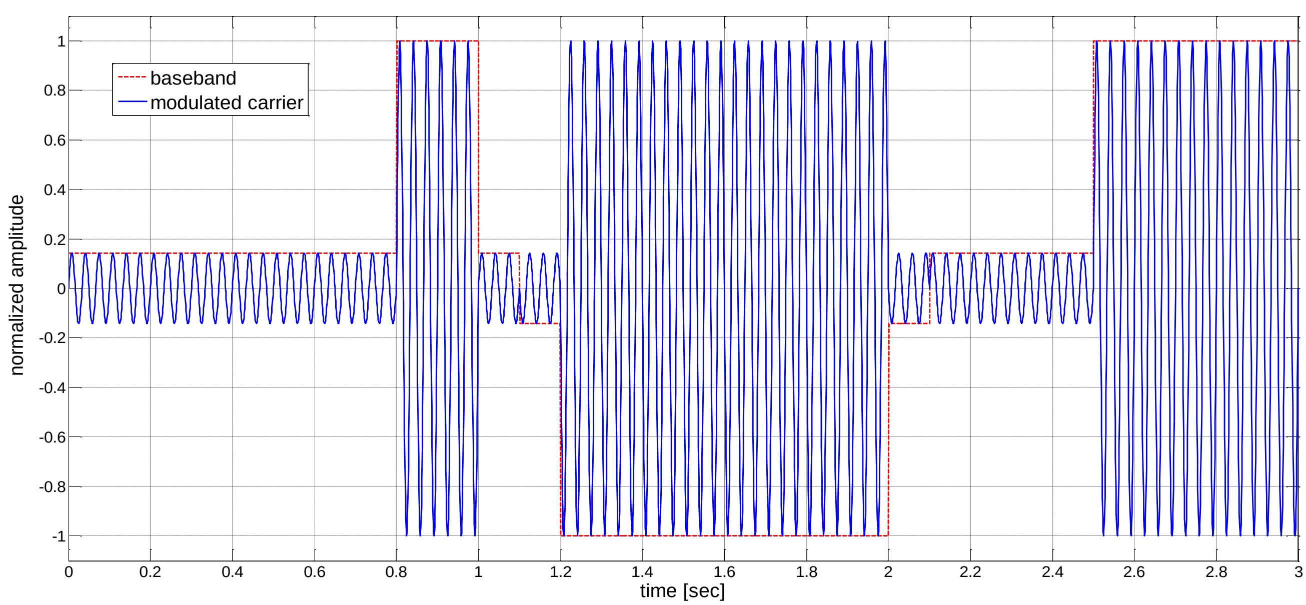

Figure 6 – An example of the broadcast signal for 3 consecutive bits (legacy: M, 0, 1 and PM: 0, 1, 0)

3. Scheduling and Types of Phase-Modulated Frames

While the legacy AM/PWM modulation is always present and the information encoded in it has not been modified in any way, the information modulated on the phase of the carrier may have several different forms, having different rates of information. For example, specific sequences, which are extended over multiple minutes while conveying less information, are periodically broadcast in place of regular one-minute frames, allowing for more robust reception at very low SNIR. Specifically, sequences of 6-minute duration are broadcast every half-hour at XX:10 UTC and XX:40 UTC. Section 7 provides a detailed description of this mode.

Messages for various purposes, such as emergency notices, may be incorporated into the broadcast and scheduled to specific instances. A message frame, transmitted at the rate of 1 bps, replaces a normal time frame. Therefore, it may not be used for time acquisition in a phase-modulation based RCC. However, it may still be used for small timing corrections, because it starts with a known synchronization word.

A message may also exceed a single frame and span over multiple frames. The broadcasting of messages will be limited to a low duty cycle (e.g., below 10% of the time), particularly during times assumed to be most critical for reception in RCC devices. Section 5 provides the bit allocation for message frames.

4. Bit Allocation and Notation in 1 bit/s Time Frame (Normal Mode)

The bit allocation for a 60-bit phase-modulated 1 bps frame dedicated to time information is described in Table 1 against the bit allocation of the legacy AM/PWM broadcast format. This section describes the contents and significance of the various fields in the one-minute time frame, while Section 5 and Table 9 describe the message frames, which may infrequently replace time frames in the PM signal.

Table 1 - Allocation of bits in one-minute **time** frame (**legacy format** in **black**, **PM** in **red**)

Second	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Legacy AM/PWM	Marker	min_40	min_20	min_10	0	min_8	min_4	min_2	min_1	Marker
Phase	**sync_T[12]**	**sync_T[11]**	**sync_T[10]**	**sync_T[9]**	**sync_T[8]**	**sync_T[7]**	**sync_T[6]**	**sync_T[5]**	**sync_T[4]**	**sync_T[3]**
Second	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Legacy AM/PWM	0	0	hour_20	hour_10	0	hour_8	hour_4	hour_2	hour_1	Marker
Phase	**sync_T[2]**	**sync_T[1]**	**sync_T[0]**	**time_par[4]**	**time_par[3]**	**time_par[2]**	**time_par[1]**	**time_par[0]**	**time[25]**	**time[0]**
Second	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Legacy AM/PWM	0	0	day_200	day_100	0	day_80	day_40	day_20	day_10	Marker
Phase	**time[24]**	**time[23]**	**time[22]**	**time[21]**	**time[20]**	**time[19]**	**time[18]**	**time[17]**	**time[16]**	**R**
Second	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**
Legacy AM/PWM	day_8	day_4	day_2	day_1	0	0	UT1_S[2]	UT1_S[1]	UT1_S[0]	Marker
Phase	**time[15]**	**time[14]**	**time[13]**	**time[12]**	**time[11]**	**time[10]**	**time[9]**	**time[8]**	**time[7]**	**R**
Second	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**
Legacy AM/PWM	UT1_C_0.8	UT1_C_0.4	UT1_C_0.2	UT1_C_0.1	0	year_80	year_40	year_20	year_10	Marker
Phase	**time[6]**	**time[5]**	**time[4]**	**time[3]**	**time[2]**	**time[1]**	**time[0]**	**dst_ls[4]**	**dst_ls[3]**	**notice**
Second	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**
Legacy AM/PWM	year_8	year_4	year_2	year_1	0	LYI	LSW	DST[1]	DST[0]	Marker
Phase	**dst_ls[2]**	**dst_ls[1]**	**dst_ls[0]**	**dst_next[5]**	**dst_next[4]**	**dst_next[3]**	**dst_next[2]**	**dst_next[1]**	**dst_next[0]**	**0**

- The significance of each of the fields in the legacy AM broadcast format is given in previous NIST publications (referenced in the Introduction section) and is not repeated here.
- Bits 29 and 39 (markers in the legacy frame), denoted “R” in the PM frame, are reserved for future use.
- Bits 4, 14, 24, 34, 44 and 54 in the legacy AM system were historically reserved for future use, but have been set permanently to 0 (i.e. high-amplitude durations of 0.8 s).

Note that bits in N-bit words are numbered from 0, for the least-significant bit (LSB), to N-1, for the most significant bit (MSB), with the MSB being transmitted first. For example, the 26-bit time word (minute counter) is numbered from 0 (LSB) to 25 (MSB), with the 25th bit (MSB) being transmitted first.

4.1. Listing of the Fields in a Time Frame

Table 2 lists the six different fields in a time frame, which add up to 60 s in duration. Since the duration of the high power level in markers, as defined by the legacy broadcast format, is only 200 ms (compared to 500 ms and 800 ms for the "1" and "0" symbols respectively), none of the time information bits rely on a marker. The purpose of each field is described in the subsequent subsections.

Table 2 - List of fields in a one-minute time frame

	purpose of field	bits allocated	total number of bits (and seconds in duration)
1	synchronization word (may include last bit of previous frame)	0-12, 59	14
2	time word (includes 5 parity bits and repeated LSB)	13-28, 30-38, 40-46	32
3	daylight saving time (DST) state and leap second notification	47-48, 50-52	5
4	advance notice for next DST transition (or message word)	53-58	6
5	NIST notice indication	49	1
6	reserved bits (coincide with markers in AM/PWM)	29, 39	2
		total:	**60**

4.2. Synchronization Word

A fixed 13-bit synchronization word, **{sync[12], sync[11],… sync[0]}**, populating bits 0-12, is used for the purpose of timing (marks the beginning of a minute) and conveys no information. The last bit in every frame (bit 59, which is a marker in the AM frame), is always 0, and may be used as an extension to the sync word, extending it to a total of 14 seconds (i.e., the last bit from a previous frame may be appended to the first 13 bits in the next frame). One of two synchronization words may be used, denoted **sync_T** and **sync_M**, for time frames and message frames respectively, as specified in Table 3.

Table 3 - 13-bit synchronization words in **time** and **message** frames

bit #	12	11	10	9	8	7	6	5	4	3	2	1	0
sync_T	**0**	**0**	**1**	**1**	**1**	**0**	**1**	**1**	**0**	**1**	**0**	**0**	**0**
sync_M	**1**	**1**	**0**	**1**	**0**	**0**	**0**	**1**	**1**	**1**	**0**	**1**	**0**

4.3. Time Word

The time word, from which the year (excluding century), the date, and the hour and minute may be extracted, is represented by a 26-bit minute counter that is reset at the beginning of year XX00, i.e., every 100 years. The current value for it in this century represents the number of minutes that have elapsed since 00:00 UTC on January 1st in the year 2000. For example, as the time turns from 21:29:59 UTC to 21:30:00 UTC on July 28th, 2016, the minute counter will be incremented from 8717609 to 8717610 (decimal). The binary representation of 8717610 will appear within the one-minute frame that starts at that instance (i.e., the 21:30:00 UTC instance is announced after it has already occurred). This timing of the frame contents with respect to the beginning of the minute frame (the "on time" mark at the beginning of the first second of the minute) is aligned with the convention defined in the legacy broadcast format.

The 26-bit time word is encoded into a 31-bit code-word, by calculating five additional parity bits that are appended to it in accordance with a linear *Hamming (31, 26)* error-correcting block code, based on the equations provided below, where the $sum_{(modulo\ 2)}$ operation is equivalent to an exclusive OR (XOR) logic operation. This provides the receiver with the capability to correct one error and to detect up to two errors in the 31-bit code-word. This 31-bit field is placed in the time frame in locations **{time_par[4], time_par[3],…time_par[0], time[25], time[24],…time[0]}**, corresponding to bits 13-18, 20-28, 30-38, and 40-46, shown in Table 1. The LSB, bit **time[0]**, is repeated on bit 19, which is a marker in the legacy broadcast format (i.e., the duration of its high power portion is only 200 ms).

- **time_par[0]** = $sum_{(modulo\ 2)}$\{**time**[23, 21, 20, 17, 16, 15, 14, 13, 9, 8, 6, 5, 4, 2, 0]\}
- **time_par[1]** = $sum_{(modulo\ 2)}$\{**time**[24, 22, 21, 18, 17, 16, 15, 14, 10, 9, 7, 6, 5, 3, 1]\}
- **time_par[2]** = $sum_{(modulo\ 2)}$\{**time**[25, 23, 22, 19, 18, 17, 16, 15, 11, 10, 8, 7, 6, 4, 2]\}
- **time_par[3]** = $sum_{(modulo\ 2)}$\{**time**[24, 21, 19, 18, 15, 14, 13, 12, 11, 7, 6, 4, 3, 2, 0]\}
- **time_par[4]** = $sum_{(modulo\ 2)}$\{**time**[25, 22, 20, 19, 16, 15, 14, 13, 12, 8, 7, 5, 4, 3, 1]\}

4.4. Indications for Daylight Saving Time (DST) and Leap Second

The 5-bit word **{dst_ls[4], dst_ls[3]… dst_ls[0]}** in locations 47-48 and 50-52 is used to indicate whether DST is in effect or not or whether it is starting or ending today, and is also used to indicate whether a positive or negative leap-second is scheduled at the end of this month (at minute 23:59 UTC). These four different possible indications for the DST state and the three for the leap second are all merged into a single 5-code word that allows for the detection of errors, particularly for the two most common combinations to be found in this 5-bit field (highlighted in Table 4). Table 4 maps each of the 12 legitimate values for the 5-bit **dst_ls** word into the corresponding values of the 2-bit indication **dst_on** and the 2-bit indication **leap_sec.** Table 5 and Table 6 list the significances for the various values of these two fields respectively.

Table 4 - Decoding table for DST and leap second indication word **{dst_ls[4], dst_ls[3]… dst_ls[0]}**

	DST and leap second code word					significance (DST and leap second bits)			
	dst_ls[4]	dst_ls[3]	dst_ls[2]	dst_ls[1]	dst_ls[0]	dst_on[1]	dst_on[0]	leap_sec[1]	leap_sec[0]
1	0	1	0	0	0	0	0	0	x
2	1	0	1	1	0	1	0	0	x
3	0	0	0	1	1	1	1	0	x
4	1	0	1	0	1	0	1	0	x
5	0	0	1	0	0	0	0	1	0
6	1	0	0	0	0	1	0	1	0
7	0	1	1	0	1	1	1	1	0
8	0	1	1	1	0	0	1	1	0
9	1	1	0	0	1	0	0	1	1
10	1	1	0	1	0	1	0	1	1
11	1	1	1	1	1	1	1	1	1
12	1	1	1	0	0	0	1	1	1

Bits **{dst_on[1], dst_on[0]}**, which are to be extracted from the **dst_ls** word according to the decoding scheme provided by Table 4, indicate the DST state, as shown in Table 5 and explained as follows: Bit **dst_on[1]** is set to 1 at 00:00 UTC on the first Sunday of the DST period (in the spring) and is reset at 00:00 UTC on the last Sunday ending the DST period (in the fall). It is to be noted that since 00:00 UTC occurs a few hours before midnight in all time zones in the United States, and the DST transitions are to be implemented after midnight, the transitions in the **dst_on[1]** bit occur a number of hours before a receiving device is required to make the appropriate 1-hour correction, depending on which time zone the device is in. For this reason, the second bit, **dst_on[0]**, serves to identify the period of time in which **dst_on[1]** has indicated that the DST period has started (or ended), but this change is not to take effect yet, since the time for that (currently set at 2 AM on a specific Sunday) has not yet been reached.

In the absence of this second bit, a device that first receives the time in the afternoon/evening on the last Saturday of the DST period (or the last one before a DST period starts), after 00:00 UTC, which is still before 6PM PST, for example, might incorrectly apply the DST time change a few hours prematurely.

Bit **dst_on[0]** follows the transitions on bit **dst_on[1]** with a delay of 24 hours (i.e., at midnight UTC between Sunday and Monday), in alignment with the corresponding 2-bit indication of the legacy AM/PWM broadcast format. The state of **dst_on[0]** allows the receiver to determine whether the DST state indicated by **dst_on[1]** has been valid for over a day, in which case the appropriate time correction is to be implemented immediately. If **dst_on[0]** indicates that the first day since the last DST transition is not over yet, then the RCC should not apply the new DST state in its time calculation until the appropriate time is reached (currently set at 2 AM in the local time zone).

Table 5 - DST state/transition word **{dst_on[1], dst_on[0]}**

dst_on[1]	dst_on[0]	significance
0	0	DST has not been in effect for over a day → Apply standard time correction with respect to UTC. Next transition is into DST
1	0	DST starts today → Do not apply the 1 hour DST correction until the appropriate time has been reached. *
1	1	DST has been in effect for more than a day → Apply one hour less of time correction with respect to UTC. Next transition is out of DST.
0	1	DST ends today → Continue to apply the DST correction and return to standard time only once the appropriate instance has been reached. *

* The combinations 01 and 10 can only be present for 24 hours (during the entire Sunday of the transition).

Bit **leap_sec[1]**, when set to 1, indicates that a leap second is scheduled at the end of the current month, as indicated in Table 6. At 00:00 UTC at the beginning of each month its value is reset to zero if no leap second is scheduled for that month (i.e. all minutes will be of 60 seconds), or is set to 1 at that instance if the last minute of that month is to be either extended to 61 seconds (i.e. positive leap second) or shortened to 59 seconds (i.e. negative leap second). Historically, only the months of June and December have been occasionally extended by one second, but the broadcast format can accommodate a leap second, either positive or negative, in any of the 12 months.

Table 6 - Leap second advance notification bit **leap_sec**

leap_sec[1]	leap_sec[0]	significance
0	x	no leap second at the end of this month
1	0	**negative** leap second scheduled for the last minute of this month
1	1	**positive** leap second scheduled for the last minute of this month

For the case of a positive leap second, the time frame representing the extended 61-second minute, starting at 23:59:00 UTC, will have bit 59 repeated (a marker in the legacy broadcast and a "0" in PM), after which bit **leap_sec[1]** will be reset to 0. For the case of a negative leap second, the time frame representing the shortened minute will have bit 59 removed, such that bit 0 of the next minute (i.e. minute 00:00 UTC of the first day of the next month) will follow immediately after bit 58.

The timing of minute-frame 00:00 UTC on the first day of the month following the implementation of the leap second, as well as the timing of the subsequent frames, will reflect the corrected time, and no further indication will be found in them for the leap second that has been implemented (the UT1 time correction information that is available in the legacy frame in the AM/PWM modulation is not provided in the PM signal).

4.5. Notice Bit

Bit 49, which is a marker in the legacy AM/PWM signal, indicates when a notice from NIST is posted at the website, as specified in Table 7. When set to 1, it may indicate that a change is imminent, a temporary shutdown is planned, or whatever other message, the details of which may be found at the station's webpage (http://www.nist.gov/pml/div688/grp40/wwvb.cfm). It is expected that most consumer market products will ignore this bit.

Table 7 - **Notice** Bit (bit 49)

Notice	significance
0	nothing to report
1	notice regarding WWVB broadcast may be found at NIST website

4.6. Advance Notification for Next DST Transition

Bits 53-58, **{dst_next[5], dst_next[4]…dst_next[0]}**, usually represent one of eight possible schedules for the upcoming DST transition (i.e., either when the DST period is to start or end), but may also convey one of 8 other possible messages, as specified in Table 8. When DST is in effect (in the spring or summer), the DST_NEXT field provides advance notification for the end of the DST period in the fall, whereas when DST is not in effect, as is the case in the winter, this field provides advance notification for the beginning of the next DST period in the upcoming spring.

For example, the start day for the DST period of the year 2013 was the second Sunday of March, and the end day was scheduled to the first Sunday of November. Therefore, the advance notification for the end day, made available once the DST period started, provides over 7 months of advance notification. With the start day of the DST period of 2014 being, again, the second Sunday of March, the advance notification for it, made available in November 2013, represents over 4 months of advance notification.

It should be noted that the DST period, which was in use prior to the one in this example, started in April and ended in October. Various factors were considered when enacting the change in the DST schedule several years ago, and the possibility of such changes being enacted again in the future was taken into account when assigning the various codewords to the possible schedules listed in Table 8.

The start/end times for the DST period are always during the night between a Saturday and a Sunday, but since the specific Sunday has changed over the years, and may change again in the future, 8 different Sundays were considered as probable candidates around the current and historic schedules. These 8 possibilities allow for any of the Sundays in March or April to serve as a start day and any of the Sundays in October or November to serve as end dates. In the unlikely scenario of a transition being scheduled to a day that is not any one of those (or a time of day that is not 1AM, 2AM or 3AM), a dedicated message (#49 in Table 8) will serve to convey that no advance notification can be provided, thus reverting to the capability of the legacy broadcast format, where the notification for the DST transition appears less than 24 hours before it is to be implemented (through the DST_LS field).

Table 8 - DST transition schedule word (and reserved messages)

	***dst_on* [1]**	**DST schedule word *dst_next* (or reserved message)**						**time and action for implementation of next DST transition**	
		[5]	**[4]**	**[3]**	**[2]**	**[1]**	**[0]**	**day**	**time (local)**
1	0	1	1	0	0	0	1	1st Sunday of March	after 0:59AM, skip from **1:00AM** to 2:00AM
2	0	1	0	0	1	1	0	**2nd Sunday of March**	
3	0	1	0	0	1	0	1	3rd Sunday of March	
4	0	0	1	0	1	0	1	4th Sunday of March	
5	0	1	1	1	1	1	0	4th Sunday since “M”	
6	0	0	1	0	1	1	0	5th Sunday since “M”	
7	0	1	1	0	1	1	1	6th Sunday since “M”	
8	0	1	1	1	1	0	1	7th Sunday since “M”	
9	0	1	0	1	0	1	0	1st Sunday of March	after 1:59AM, skip from **2:00AM** to 3:00AM
10	0	**0**	**1**	**1**	**0**	**1**	**1**	**2nd Sunday of March**	
11	0	0	0	1	1	1	0	3rd Sunday of March	
12	0	0	0	0	0	0	1	4th Sunday of March	
13	0	0	0	0	0	1	0	4th Sunday since “M”	
14	0	0	0	1	0	0	0	5th Sunday since “M”	
15	0	0	0	1	1	0	1	6th Sunday since “M”	
16	0	1	0	1	0	0	1	7th Sunday since “M”	
17	0	0	0	0	1	0	0	1st Sunday of March	after 2:59AM, skip from **3:00AM** to 4:00AM
18	0	1	0	0	0	0	0	**2nd Sunday of March**	
19	0	1	1	0	1	0	0	3rd Sunday of March	
20	0	1	0	1	1	0	0	4th Sunday of March	
21	0	1	1	1	0	0	0	4th Sunday since “M”	
22	0	0	1	0	0	0	0	5th Sunday since “M”	
23	0	1	1	0	0	1	0	6th Sunday since “M”	
24	0	0	1	1	1	0	0	7th Sunday since “M”	
25	1	1	1	0	1	1	1	4th Sunday before “N”	after 0:59AM, instead of **1:00AM** move back to 0:00AM
26	1	0	1	0	1	0	1	3rd Sunday before “N”	
27	1	1	1	0	0	0	1	2nd Sunday before “N”	
28	1	0	1	0	1	1	0	1st Sunday before “N”	
29	1	1	0	0	1	1	0	**1st Sunday of November**	
30	1	1	1	1	1	1	0	2nd Sunday of November	
31	1	1	0	0	1	0	1	3rd Sunday of November	
32	1	1	1	1	1	0	1	4th Sunday of November	
33	1	0	0	1	1	0	1	4th Sunday before “N”	after 1:59AM, instead of **2:00AM** move back to 1:00AM
34	1	0	0	0	0	0	1	3rd Sunday before “N”	
35	1	1	0	1	0	1	0	2nd Sunday before “N”	
36	1	0	0	1	0	0	0	1st Sunday before “N”	
37	1	**0**	**1**	**1**	**0**	**1**	**1**	**1st Sunday of November**	
38	1	0	0	0	0	1	0	2nd Sunday of November	
39	1	0	0	1	1	1	0	3rd Sunday of November	
40	1	1	0	1	0	0	1	4th Sunday of November	
41	1	1	1	0	0	1	0	4th Sunday before “N”	after 2:59AM, instead of **3:00AM** move back to 2:00AM
42	1	1	0	1	1	0	0	3rd Sunday before “N”	
43	1	0	0	0	1	0	0	2nd Sunday before “N”	
44	1	0	1	0	0	0	0	1st Sunday before “N”	
45	1	1	0	0	0	0	0	**1st Sunday of November**	
46	1	1	1	1	0	0	0	2nd Sunday of November	
47	1	1	1	0	1	0	0	3rd Sunday of November	
48	1	0	1	1	1	0	0	4th Sunday of November	
49	**x**	1	0	0	0	1	1	DST transition occurs at different time*	
50	**x**	0	0	0	1	1	1	no DST period scheduled this year	
51	**x**	1	0	1	1	1	1	DST in effect for this whole year	
52	**x**	1	1	0	0	0	0	reserved 1	
53	**x**	1	0	0	1	0	0	reserved 2	
54	**x**	0	1	0	1	0	0	reserved 3	
55	**x**	1	1	0	1	1	0	reserved 4	
56	**x**	1	1	0	1	0	1	reserved 5	

x = either 0 or 1, "M" = first Sunday in March, "N" = first Sunday in November

* DST transition to occur outside of defined schedules, so no advance notification available.

As can be seen in Table 8, 24 combinations of day and time are supported for possible start/end times for the DST period, resulting in a total of 48 different 6-bit combinations. Historically, the DST transition in the US has been implemented at 2 AM (local time), but specific codewords have also been reserved for the possibility of this time being set at 1 AM or 3 AM, as is done in other countries.

For combinations 49-56 the **dst_on** state has no relevance, as these do not represent specific start/end times. Message 49 is reserved for the case of a new DST schedule being enacted that is not among the 24 predefined ones, message 50 is reserved for the possibility of DST being cancelled (i.e. standard time is maintained throughout the year), and message 51 has been reserved for the case of DST being permanently in effect (i.e. time is set one hour ahead of standard time). Additionally, five different words (messages 52-56) have been reserved, for which specific messages may be defined in the future, such as emergency messages.

5. Bit Allocation in Message Frame

Table 9 specifies the bit allocation for the message frames. The message frame starts with a 13-bit synchronization word, as defined in subsection 4.2. The LSB of the time word, **time[0]**, is available on bit 19 (marker) in message frames too, as in time frames. This allows receivers that are resolving timing uncertainties only below one minute to be able to use message frames for that purpose, assuming that they are experiencing sufficiently high SNIR for this single 200 ms symbol to suffice.

The **Notice** bit in location 49 (marker), functions in message frames as defined for time frames in subsection 4.5.

The 42 bit word in the remaining locations, **{data[41], data [40],…data[0]}**, defines the contents of the message and may contain fields indicating the address to which the message is intended, the total length of the message (may extend over multiple frames), etc.

Table 9 - Allocation of bits in one-minute **message** frame - (**legacy format** in **black**, **PM** in **blue)**

Second	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Legacy AM/PWM	Marker	min_40	min_20	min_10	0	min_8	min_4	min_2	min_1	Marker
Phase	**sync_M[12]**	**sync_M[11]**	**sync_M[10]**	**sync_M[9]**	**sync_M[8]**	**sync_M[7]**	**sync_M[6]**	**sync_M[5]**	**sync_M[4]**	**sync_M[3]**
Second	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Legacy AM/PWM	0	0	hour_20	hour_10	0	hour_8	hour_4	hour_2	hour_1	Marker
Phase	**sync_M[2]**	**sync_M[1]**	**sync_M[0]**	**data[41]**	**data[40]**	**data[39]**	**data[38]**	**data[37]**	**data[36]**	**time[0]**
Second	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Legacy AM/PWM	0	0	day_200	day_100	0	day_80	day_40	day_20	day_10	Marker
Phase	**data[35]**	**data[34]**	**data[33]**	**data[32]**	**data[31]**	**data[30]**	**data[29]**	**data[28]**	**data[27]**	**R**
Second	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**
Legacy AM/PWM	day_8	day_4	day_2	day_1	0	0	UT1_S[2]	UT1_S[1]	UT1_S[0]	Marker
Phase	**data[26]**	**data[25]**	**data[24]**	**data[23]**	**data[22]**	**data[21]**	**data[20]**	**data[19]**	**data[18]**	**R**
Second	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**
Legacy AM/PWM	UT1_C_0.8	UT1_C_0.4	UT1_C_0.2	UT1_C_0.1	0	year_80	year_40	year_20	year_10	Marker
Phase	**data[17]**	**data[16]**	**data[15]**	**data[14]**	**data[13]**	**data[12]**	**data[11]**	**data[10]**	**data[9]**	**notice**
Second	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**
Legacy AM/PWM	year_8	year_4	year_2	year_1	0	LYI	LSW	DST[1]	DST[0]	Marker
Phase	**data[8]**	**data[7]**	**data[6]**	**data[5]**	**data[4]**	**data[3]**	**data[2]**	**data[1]**	**data[0]**	**0**

6. Example for One-Minute Broadcast Time Frame

Table 10 clarifies the use of the different fields in the PM broadcast format through an example, which is explained here. For binary words shown in this example in "{ }", the most-significant bit (MSB) appears to the left and is broadcast first. The date and time encoded in this example correspond to July 4, 2012 at 17:30 UTC, and would have been broadcast between the instances 17:30:00 and 17:31:00. In other words, the minute being encoded in the broadcast is the one that has already started, as has always been the case with the legacy broadcast format.

Table 10 - Example of one-minute time frame **(legacy format in black, PM in red)**

Second	0	1	2	3	4	5	6	7	8	9
Legacy AM/PWM	Marker	min_40	min_20	min_10	0	min_8	min_4	min_2	min_1	Marker
bit value	-	0	1	1	0	0	0	0	0	-
Phase	sync_T[12]	sync_T[11]	sync_T[10]	sync_T[9]	sync_T[8]	sync_T[7]	sync_T[6]	sync_T[5]	sync_T[4]	sync_T[3]
bit value	0	0	1	1	1	0	1	1	0	1

Second	10	11	12	13	14	15	16	17	18	19
Legacy AM/PWM	0	0	hour_20	hour_10	0	hour_8	hour_4	hour_2	hour_1	Marker
bit value	0	0	0	1	0	0	1	1	1	-
Phase	sync_T[2]	sync_T[1]	sync_T[0]	time_par[4]	time_par[3]	time_par[2]	time_par[1]	time_par[0]	time[25]	time[0]
bit value	0	0	0	1	0	0	1	0	0	0

Second	20	21	22	23	24	25	26	27	28	29
Legacy AM/PWM	0	0	day_200	day_100	0	day_80	day_40	day_20	day_10	Marker
bit value	0	0	0	1	0	1	0	0	0	-
Phase	time[24]	time[23]	time[22]	time[21]	time[20]	time[19]	time[18]	time[17]	time[16]	R
bit value	0	0	1	1	0	0	1	0	0	0

Second	30	31	32	33	34	35	36	37	38	39
Legacy AM/PWM	day_8	day_4	day_2	day_1	0	0	UT1_S[2]	UT1_S[1]	UT1_S[0]	Marker
bit value	0	1	1	0	0	0	1	0	1	-
Phase	time[15]	time[14]	time[13]	time[12]	time[11]	time[10]	time[9]	time[8]	time[7]	R
bit value	0	1	1	0	0	0	1	1	0	1

Second	40	41	42	43	44	45	46	47	48	49
Legacy AM/PWM	UT1_0.8	UT1_0.4	UT1_0.2	UT1_0.1	0	year_80	year_40	year_20	year_10	Marker
bit value	0	1	0	0	0	0	0	0	1	-
Phase	time[6]	time[5]	time[4]	time[3]	time[2]	time[1]	time[0]	dst_ls[4]	dst_ls[3]	notice
bit value	0	0	1	1	0	1	0	0	0	1

Second	50	51	52	53	54	55	56	57	58	59
Legacy AM/PWM	year_8	year_4	year_2	year_1	0	LYI	LSW	DST[1]	DST[0]	Marker
bit value	0	0	1	0	0	1	0	1	1	-
Phase	dst_ls[2]	dst_ls[1]	dst_ls[0]	dst_next[5]	dst_next[4]	dst_next[3]	dst_next[2]	dst_next[1]	dst_next[0]	0
bit value	0	1	1	0	1	1	0	1	1	0

The encoded time is referenced to minute 0, which started at the instance 00:00:00 UTC on January 1st in the year 2000. Therefore, this example date and time correspond to the 6,578,970th minute since that instance, when considering 60 minutes per hour and 24 hours per day. Hence, the 26-bit field **time[25:0]**, corresponding to this instance, holds the binary representation equivalent to the decimal value 6,578,970. Bit **time[25]**, in location 18, represents the MSB and is zero in this example (will not be set to one until after the middle of the century), and bit **time[0]**, in location 46, represents the LSB, and is zero in this example since this minute count is an even number. Note that **time[0]** also appears in location 19, which is a marker in the legacy AM format. Using the parity equations provided in section 4.3, the parity bits for the time-word are found to be {1 0 0 1 0}, placed in **time_par[4:0]**, where **time_par[4]** is the MSB.

The sync word bits are represented by the 13-bit word **sync_T[12:0]** (since this is a time information frame rather than a message). These 13 bits are independent of the time and have the fixed values of {0 0 1 1 1 0 1 1 0 1 0 0 0}, as specified in Table 3.

Since July 4th falls while daylight-saving-time (DST) has been in effect for over one day, the **dst_ls[4:0]** bits are set to { 0 0 0 1 1 } indicating, as shown in Table 4, that the DST state bits **dst_on[1:0]** are both set to 1, and **leap_sec[1]** is set to 0. The **dst_on[1:0]** bits, being set to { 1 1 }, signify that DST has been in effect for more than one day, and that the next DST transition would be the end of the DST period. The **leap_sec[1]** notification bit being 0 indicates, as shown in Table 4, that there will be no leap second added to the last minute of this month (July). It is to be noted that the previous month, June 2012, had a leap second added at its end (the minute starting at 23:59:00 UTC on June 30th had 61 seconds), following which the leap second notification bit **leap_sec[1]** was to be reset from 1 to 0 until another leap second is decided upon and is to be announced.

The **dst_next[5:0]** field is set to {0 1 1 0 1 1} which, as shown in Table 8, indicates, along with **dst_on[1]** being set to 1, that the transition out of DST is to occur on the first Sunday of November at 02:00AM local time (at the local time zone, if DST is observed, the time is to be moved back to 01:00AM).

The notice bit in location 49, which is a marker, is set to 1, indicating the NIST has a notice posted at http://www.nist.gov/pml/div688/grp40/wwvb.cfm, notifying of changes to the WWVB broadcast signal, anticipated downtime, etc.

In this example, the bits at locations 29 and 39, which are markers, are arbitrarily set to 0 and 1, respectively, carrying no information at this time, as these are reserved for future used.

The bit in location 59, which is a marker in the legacy AM format, is always set to 0, unless the one-minute frame is overridden by a multi-minute sequence.

The assignment of the AM bits adheres to the legacy broadcast format, which may be found at this link: http://tf.nist.gov/general/pdf/1383.pdf.

7. Extended (Reduced-Rate) Symbols

This section describes the structure, data content, and timing of extended symbols that are currently part of the enhanced phase-modulation (PM) based WWVB broadcast. Various features are expected to be added to the extended-transmission mode, which will appear in a future release of this document.

The extended symbols provide further enhancement of the reception robustness due to the limited amount of information they convey and their extended duration, representing correspondingly greater energy. This mode is based on a predefined set of 124 symbols (bit-sequences) that span 6-minutes in duration, of which one is broadcast every half hour. Hence, when compared to a normal one-minute frame, these 6-minute symbols contain 6× more energy and represent much less information (only the time of day), resulting in over an order of magnitude of gain in the link budget.

Since the daylight saving time (DST) state must accompany the time information, 48 different symbols, representing each of the 48 half-hour instances of a day, would not suffice. Therefore, additional symbols are used to allow inclusion of the DST information, arriving at a total of 124 different symbols.

The DST state in the legacy broadcast format, as well as in the one-minute PM frame, is based on two bits that are sequentially set at the beginning and end of the Sunday of the DST transition (i.e. at 00:00 UTC). This 2-bit indication prevents an RCC from applying a DST transition prematurely, which could have happened if only one bit were to be considered, as explained in subsection 4.4.

7.1. Scheduling of the 6-Minute Extended Symbols

Every 30 minutes, at XX:10 UTC and at XX:40 UTC, a unique sequence is broadcast, having a total of 360 bits (i.e. 6 minutes in duration). The sequence to be broadcast is chosen from a set of 124 sequences according to the time of day and the state of DST indication bits DST_ON[1] and DST_ON[0], as specified in Table 11.

7.2. Structure of Extended Symbols

Each of the 124 extended symbols, spanning 6 minutes, comprises 3 concatenated sequences creating a sequence of length 127 + 106 + 127 = 360 bits (i.e. a duration of 360 s, or 6 minutes), as illustrated in Figure 7. The first sequence is a 127-bit pseudo-random bit-sequence (PRBS) that is generated in accordance with the time information that is being broadcast. The second sequence is a 106-bit fixed timing word, which is specified in Table 12. The third sequence is a mirrored form of the first 127-bit PRBS (i.e. with the bits in reversed order). This provides benefits in timing extraction.

The PRBS used in each extended symbol is chosen based on the time of day and the state of DST, such that it conveys the time information, whereas the fixed sequence of 106 bits only conveys timing.

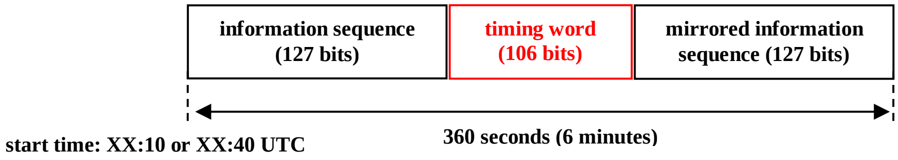

Figure 7 – Structure of 6-minute extended symbol

The 124 different information symbols, represented by the 127-bit sequences, are based on the 7th order generating polynomial $g(x) = x^7 + x^6 + x^5 + x^2 + 1$ with different initialization words, resulting in different cyclic rotations of the same 127-bit sequence. The sequence for the first symbol (#1 in Table 11, corresponding to 00:10 UTC with DST not in effect) is based on initialization word {1 1 1 1 1 1 1}, resulting in the sequence shown below, and each subsequent sequence is shifted by one bit from the previous sequence (one left shift). For example, the second symbol (#2 in Table 11) could be created by initializing the linear-feedback shift-register (LFSR) based generator, shown in Figure 8, with the initial state {1 1 1 1 1 1 0}, with the element written on the right corresponding to the LSB in the LFSR. This sequence is also provided below in its entirety.

<u>Sequence #1 - 00:10 UTC, DST = 0 0 (i.e. DST not in effect)</u>

1 1 1 1 1 1 1 0 0 1 1 0 1 1 0 1 0 1 0 1 0 0 0 1 0 0 1 0 0 1 1 0 0 1 1 1 1 0 0 0 1 1 1
0 1 1 1 0 1 0 1 1 1 1 0 1 0 0 1 0 1 1 0 0 1 0 1 0 0 1 1 1 0 0 1 0 0 0 1 1 0 0 0 1 0 1
1 1 0 0 0 0 1 0 0 0 0 1 1 0 1 0 0 0 0 0 1 1 1 1 1 0 1 1 0 0 0 0 0 0 1 0 1 0 1 1 0

<u>Sequence #2 - 00:10UTC, DST=11 (i.e. DST in effect)</u>

1 1 1 1 1 1 0 0 1 1 0 1 1 0 1 0 1 0 1 0 0 0 1 0 0 1 0 0 1 1 0 0 1 1 1 1 0 0 0 1 1 1 0
1 1 1 0 1 0 1 1 1 1 0 1 0 0 1 0 1 1 0 0 1 0 1 0 0 1 1 1 0 0 1 0 0 0 1 1 0 0 0 1 0 1 1
1 0 0 0 0 1 0 0 0 0 1 1 0 1 0 0 0 0 0 1 1 1 1 1 0 1 1 0 0 0 0 0 0 1 0 1 0 1 1 0 1

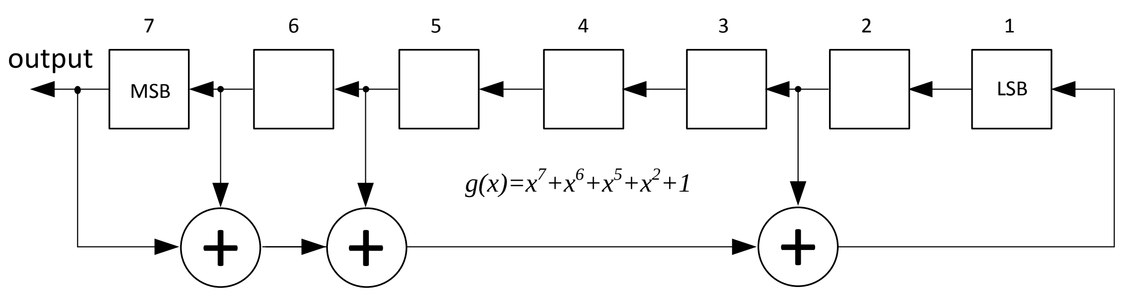

Figure 8 – Linear feedback shift register (LFSR) for generation of 127-bit sequences

Table 11 - Broadcast schedule for extended symbols (360-bit sequences)

type of day →		outside of DST period	during DST period	on Sunday of transition into DST in spring	on Sunday of transition out of DST in fall
DST bits	DST_ON[1]	0	1	1	0
	DST_ON[0]	0	1	0	1
		sequence #	**sequence #**	**sequence #**	**sequence #**
time (UTC)	0:10:00	1	2	1	2
	0:40:00	3	4	3	4
	1:10:00	5	6	5	6
	1:40:00	7	8	7	8
	2:10:00	9	10	9	10
	2:40:00	11	12	11	12
	3:10:00	13	14	13	14
	3:40:00	15	16	15	16
	4:10:00	17	18	97	98
	4:40:00	19	20	99	100
	5:10:00	21	22	101	102
	5:40:00	23	24	103	104
	6:10:00	25	26	105	106
	6:40:00	27	28	107	108
	7:10:00	29	30	109	110
	7:40:00	31	32	111	112
	8:10:00	33	34	113	114
	8:40:00	35	36	115	116
	9:10:00	37	38	117	118
	9:40:00	39	40	119	120
	10:10:00	41	42	121	122
	10:40:00	43	44	123	124
	11:10:00	45	46	46	45
	11:40:00	47	48	48	47
	12:10:00	49	50	50	49
	12:40:00	51	52	52	51
	13:10:00	53	54	54	53
	13:40:00	55	56	56	55
	14:10:00	57	58	58	57
	14:40:00	59	60	60	59
	15:10:00	61	62	62	61
	15:40:00	63	64	64	63
	16:10:00	65	66	66	65
	16:40:00	67	68	68	67
	17:10:00	69	70	70	69
	17:40:00	71	72	72	71
	18:10:00	73	74	74	73
	18:40:00	75	76	76	75
	19:10:00	77	78	78	77
	19:40:00	79	80	80	79
	20:10:00	81	82	82	81
	20:40:00	83	84	84	83
	21:10:00	85	86	86	85
	21:40:00	87	88	88	87
	22:10:00	89	90	90	89
	22:40:00	91	92	92	91
	23:10:00	93	94	94	93
	23:40:00	95	96	96	95

Table 12 - Fixed 106-bit timing word

Second	0	1	2	3	4	5	6	7	8	9
0	1	1	0	1	0	0	0	1	1	1
10	0	1	0	1	1	0	0	1	0	1
20	1	0	0	1	1	0	1	1	1	0
30	0	0	1	1	0	0	0	0	1	0
40	1	1	0	1	0	0	1	1	1	0
50	1	0	0	1	0	1	0	1	0	0
60	0	0	1	0	1	1	1	0	0	0
70	1	0	1	1	0	1	0	1	1	0
80	1	1	0	1	1	1	1	1	1	1
90	1	0	0	0	0	0	0	1	0	0
100	1	0	0	1	0	0				

7.3. DST Indication Method

The DST indication method that is used both in the legacy AM and in the normal-mode PM frames uses two bits in order to represent the 4 possibilities: “DST not in effect”, “DST starts today”, “DST in effect”, and “DST ends today”. Considering 48 possible times of day (XX:10 and XX:40), the addition of 2 independent bits would have resulted in a total of $4 \times 48 = 192$ combinations, which is beyond the number of sequence phases (i.e. symbols) that can be represented by cyclic rotations of a PN sequence of 127 bits. Hence, the DST indication in the extended symbols was effectively reduced to less than 2 bits, such that only during a certain part of the evening/night (in all North American time zones) a receiver may be informed of the two possibilities “DST starts today” and “DST ends today”, each of which may exist only during one day in a year. The 6½ hour interval during which such information is provided is **04:10 – 10:40** (UTC), chosen such that in all US time zones where DST is followed, an RCC may receive a notification prior to 2 AM, the local time at which DST transitions are currently implemented.

The use of the states “DST starts today” and “DST ends today” avoids the premature implementation of a DST transition in an RCC that first receives less than a day before a transition. In such case, the RCC must not implement the new DST state until 2 AM local time. Premature implementation of the DST transition would result in the RCC having the incorrect time (by one hour) for several hours, until 2 AM in that time zone. The encoding employed in the extended symbols provides a slightly different solution for avoiding such premature implementation of a DST transition. It is to be noted that the date information and the advance notice for a DST transition, which appear in the one-minute PM frame, are not incorporated in the extended symbols. Therefore, an RCC that has not been initialized manually or through the successful reception of the one-minute PM frame, and operates solely based on the reception of extended symbols, could apply a prudent time-acquisition strategy in order to avoid premature implementation of a DST transition, as follows: If the RCC were to acquire the time between 00:10 UTC and 03:40 UTC or between 11:10 UTC and 23:40 UTC (i.e. based on a sequence that is either in the group 1-16 or in the group 45-96 of Table 11), it would have to receive again at (or after) 04:10 UTC in order to be informed of a DST transition that may occur that night. Once the RCC experiences a DST transition, it may assume that another such transition won’t occur for a few months.

The symbols transmitted on most days of the year (with the exception of the two DST transition Sundays) are the 96 first, as can be seen in Table 11. Half of these indicate that DST has been in effect for over a day and the other half are used when DST has not been effect for over a day. Whenever any of these symbols is received, the RCC may immediately implement the appropriate time correction with respect to UTC (i.e. the RCC applies the DST one-hour correction according to the LSB of the index of the received symbol, and will unconditionally produce the correct time).

For the Sundays of the DST transitions, 4 hours and 10 minutes after the transition in bit DST_ON[1], i.e. at 04:10 UTC on that Sunday, for a duration of 6.5 hours, i.e. until 10:40 UTC, the 28 symbols that are normally transmitted during that period of time are replaced by symbols 97-124 (highlighted in green and in orange in Table 11). These symbols indicate that a transition is to be implemented that night, allowing the RCC to schedule the 1-hour correction to 2 AM in the local time zone, if the sequence has been detected before that time, or to implement the correction immediately if it is after 2 AM local time.

The time zone in which the DST correction is to occur first is that of the French territory Saint-Pierre and Miquelon (island south of the Canadian island Newfoundland). When DST is not in effect, the time in this time zone is UTC-3. When DST is in effect, it is UTC-2. The first symbol indicating the transition into DST is scheduled to occur at 04:10 UTC, which is 50 minutes before the transition into DST in this time zone in the spring, and is 10 minutes after the transition out of DST in the fall. This dictated the timing designated to symbols #97 and #98.

The last time zone that follows this DST scheme is the Hawaii-Aleutian time-zone (one time-zone west of Alaska Time, i.e. UTC-10) since Hawaii does not observe DST. However, these Islands are not densely inhabited and the normal mode should be received there. Since Alaska Time is UTC-9, symbol #123 would be received there 20 minutes before the transition into DST (the next symbol, which would be #46, would be received 10 minutes after DST is to be implemented). When transitioning out of DST, the correct time to perform the transition there (2 AM local time) would be 10:00 UTC.