NIST Time and Frequency Broadcasts from Radio Stations WWVB, WWV, and WWVH

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ABSTRACT

The National Institute of Standards and Technology (NIST) radio stations WWVB, WWV, and WWVH provide a convenient link to the national standards of time and frequency maintained at NIST. In recent years, NIST has made significant improvements to these stations to better serve users. The most noticeable improvement has been a 7 dB boost in radiated power to the WWVB signal. This power increase has substantially increased the coverage area stimulating more use of the signal. In the next few years, the number of consumer-oriented WWVB receivers is expected to number in the millions of units. This paper presents the history, operation, and use of these NIST time and frequency broadcasts.

1. INTRODUCTION

The International Telecommunication Union (ITU) has certain broadcast frequencies reserved for standard time and frequency broadcasts. The ITU, an agency of the United Nations, has divided the globe into three regions as shown in Figure 1. In order to minimize interference between radio broadcasts, frequency allocations are determined for each region at the World Administrative Radio Conferences held every 2 years. Very low frequency (VLF) and low frequency (LF) broadcasts of time and frequency in all three regions are 14-19.95 kHz, 20 kHz, and 20.05-70 kHz. Region 1 also uses 72-84 kHz and 86-90 kHz. The frequencies for high frequencies (HF) are 2500 kHz, 5000 kHz, 10 000 kHz, 15 000 kHz, 20 000 kHz, and 25 000 kHz. NIST uses 60 kHz, 2500 kHz, 5000 kHz, 10 000 kHz, 15 000 kHz, and 20 000 kHz for its broadcasts of time and frequency.

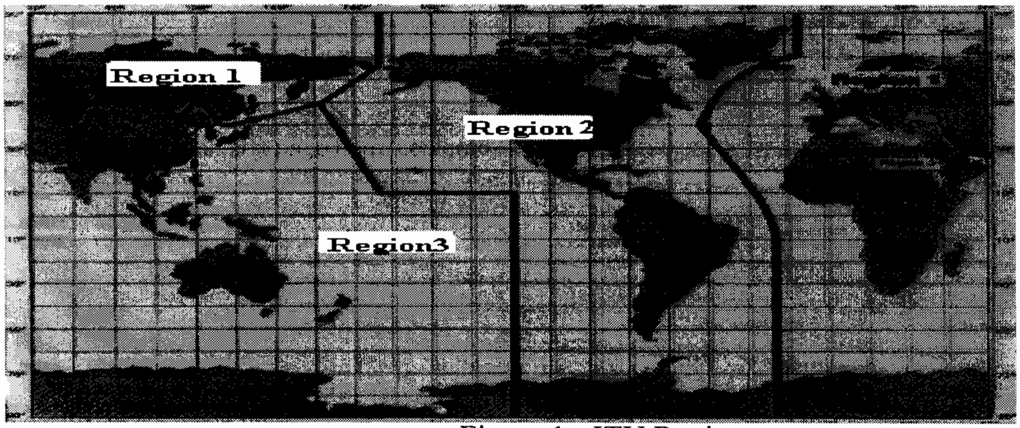


Figure 1 - ITU Regions

2. NIST Radio Station WWVB

NIST radio station WWVB is located near Fort Collins, Colorado. WWVB continuously broadcasts time and frequency signals at 60 kHz, in the LF part of the radio spectrum. The WWVB signal includes a time code that is used to automatically synchronize millions of radio clocks every day in the continental United States and neighboring areas. These radio clocks include wristwatches, desk clocks, alarm clocks, wall clocks, and clocks integrated into other devices such as televisions and radios. In addition, calibration and testing laboratories use the 60 kHz carrier frequency from WWVB to calibrate electronic equipment and frequency standards.

2.1 History of WWVB

The first standard frequency broadcast of 60 kHz started in July 1956, from Station KK2XEI located in Boulder, Colorado, at the National Bureau of Standards (NBS). This experimental broadcast using a 2 kW transmitter was the forerunner of WWVB. The radiated signal was less than 2 watts but was monitored at Harvard University in Massachusetts. The purpose of this experimental transmission was to show that the frequency error due to Doppler shift induced by the ionosphere was relatively small.

NBS, currently NIST, also began an experimental VLF standard frequency broadcast called WWVL from a valley span antenna at Sunset, Colorado, just northwest of Boulder in April 1960. This signal, though less than 15 watts (W) radiated, was observed in New Zealand.

In 1962 NBS began construction of a transmitter site north of Fort Collins, Colorado, to be the new home of radio stations WWVB and WWVL. The 390 acre, 156 hectare, site was selected because of its exceptionally high ground conductivity, which was due to the high alkalinity of the soil. WWVB became operational at the Fort Collins site on July 5, 1963, transmitting a 7 kW standard 60 kHz signal. Housed in the same transmitter building was WWVL, which began transmitting a 500 W standard 20 kHz signal in August 1963.

On July 1, 1965, a time code was added to the WWVB broadcast. This time code is sent in binary-coded-decimal (BCD) format. During the mid-1960s improvements to the station raised the power level to approximately 13 kW and the power of the WWVL signal was raised to 1 kW. On July 1, 1972, the WWVL transmissions were discontinued. During the 1990s WWVB went through a major upgrade that replaced and modernized the transmitting system and improved the efficiency of the antenna system. The radiated power was increased from 13 kW in the early 1990s to 50 kW by 1999.

2.2 WWVB Antenna System

When the new site for the NBS stations was established in 1962, two identical antennas were constructed. The north antenna was built for the WWVL 20 kHz broadcast, and the south antenna was built for the WWVB 60 kHz broadcast. The configuration chosen for each antenna was a top loaded dipole. Each antenna consists of four 122 m masts arranged in a diamond shape (Figure 2). Suspended between the four towers is a system of heavy cables, often called a capacitance hat, top hat, or topload. This top hat is electrically isolated from the towers, and it is electrically connected to a downlead that is suspended from the center of the top hat. The downlead is the radiating element.

Ideally, to have an efficient radiating system, the radiating element needs to be at least one-quarter wavelength long. At 60 kHz, where the wavelength is nearly 5 km (and nearly 15 km for 20 kHz) it is impractical to have the desired one-quarter wavelength antenna since the downlead would need to be 1,250 m tall. However, a compromise can be made by building the radiating element as tall as possible and adding some of the missing length horizontally to the top of this vertical dipole. Even with the top load the WWVB and WWVL antennas are still only a fraction of the transmitted wavelength, and are inherently capacitive with a small radiation resistance.

The downlead of each antenna is terminated at its own helix house under the top hats. Both helix houses contain a variometer (variable inductor) which is used to cancel the capacitance of the short antenna and to tune the antenna system during periods when snow or wind loads the antenna.

When WWVL ceased operation in 1972, its 20 kHz antenna was rematched to a WWVB transmitter to operate as an emergency standby 60 kHz antenna. A distance of 850 meters separates the radiating elements of these two antennas.

Antennas that are less than one-quarter wavelength have only moderate efficiency. Efficiency is determined by taking the ratio of radiation resistance (R_{rad}) to gross resistance ($R_{gross} = R_{rad}$ + resistance due to losses). At 60 kHz, the efficiency of the north antenna system was determined to be 50.6% (R_{gross}=0.91 ohms, R_{rad}=0.46 ohms). The south antenna at 60 kHz had an efficiency of 57.5% (R_{gross}=0.80 ohms, R_{rad}=0.46 ohms).

Using both antennas permits using independent transmitters to drive the north antenna and the south antenna. The advantage of transmitting from both antennas is that the combined system produces a total efficiency of 65%. With a forward power from each transmitter of only 38 kW, the combination of the two transmitting systems produces a radiated power of 50 kW.

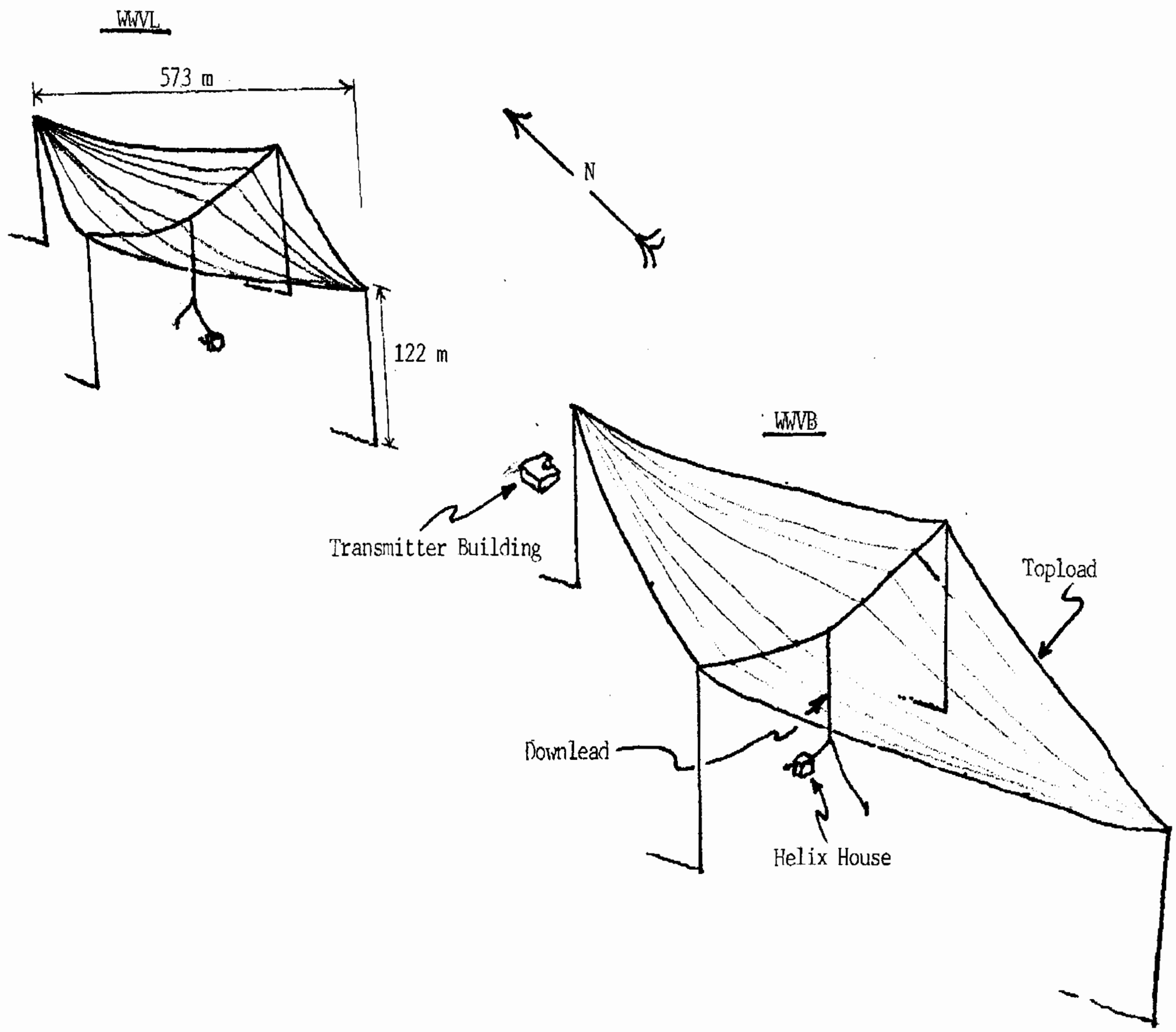


Figure 2

2.3 WWVB Transmitters

There are a total of three LF transmitters at the WWVB site. Two are in constant operation and one serves as a standby. Each LF transmitter consists of two identical power amplifiers (PA), which are combined to produce a significantly amplified signal sent to the antenna. Each of the two PAs consists of two 4CX15000 tubes in a push-pull configuration. The front end of each transmitter has been replaced with a solid-state amplifier that provides a 200 W drive signal to the grids of the PA tubes, which are biased as class AB_1 amplifiers. Each of the transmitters is approximately 40% efficient.

2.4 WWVB Propagation

The propagation of VLF/LF electromagnetic energy has many properties that make VLF/LF well suited for the transfer of time and frequency. At these longer wavelengths, losses in the earth's surface are low. Thus, the ground wave can travel well for thousands of kilometers and only moderate amounts of power are needed to cover large portions of a hemisphere. Other advantages include a stable path, low attenuation by the atmosphere, and reliability during ionospheric disturbances.

2.5 WWVB Coverage Area

The time signal from WWVB propagates primarily by ground wave and is less affected by the ionosphere. Reception is possible throughout most of the hemisphere. Computer models have been generated to predict signal strength at different times during the day for selected cities. (Figure 3) Note that the coverage area is much greater at night.

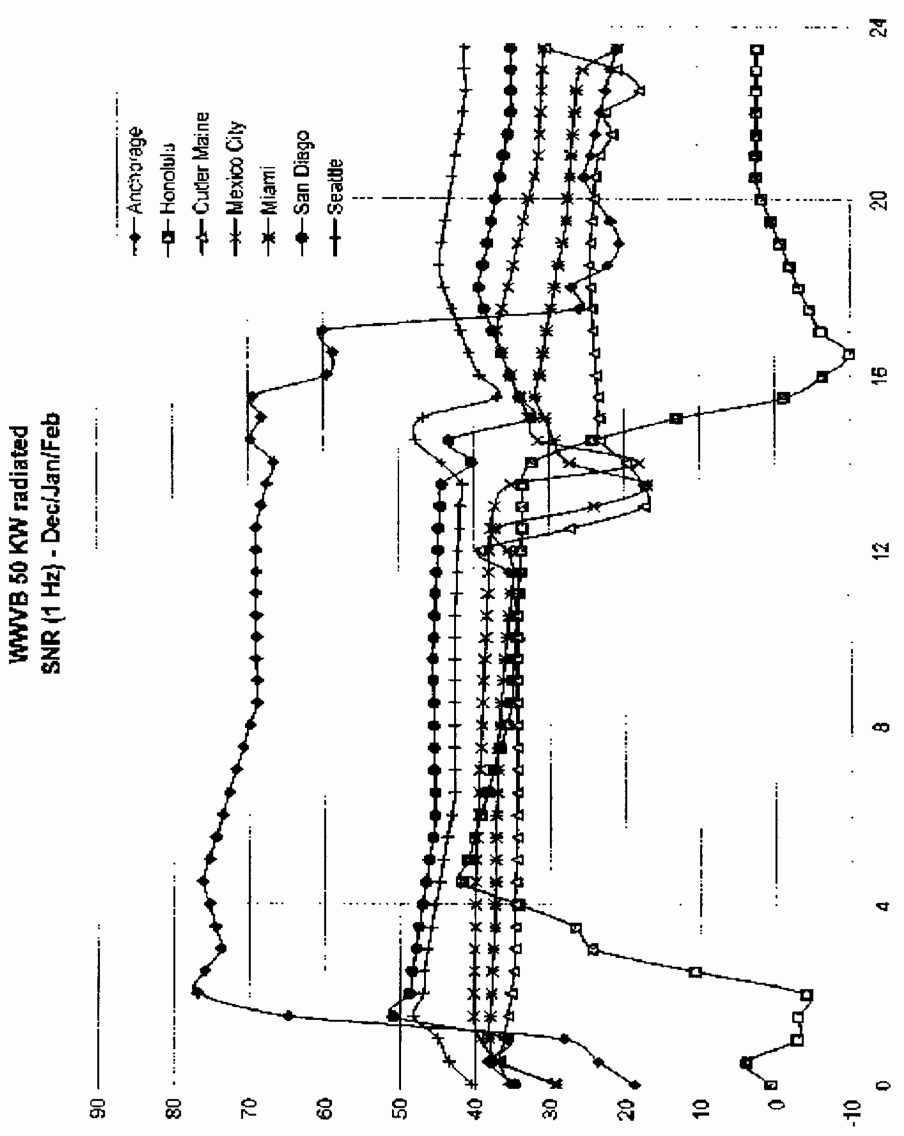


Figure 3 – (Time "axis" is in UTC)

As previously mentioned, the dual antenna operation of WWVB affords greater efficiency. An added benefit of this dual operation is that, due to the antenna pattern "lobes" created by the dual antennas, there is a 1 dB increase of power in the east to west direction over that of an omnidirectional pattern. This partially matches the need for reaching out further in these directions.

2.6 WWVB Receivers

In the past, users of WWVB were primarily groups that could afford the large and costly systems required for receiving and decoding the accurate and precise time. Much of the public was interested in knowing the "exact" time, but was limited to dial-up phone service or short-wave radio (WWV or WWVH) in order to acquire the time of day to set their clocks. This was inconvenient because timepieces drift, their power source is sometimes interrupted, and occasional adjustments need to be made (e.g. daylight saving time, leap seconds, or leap years). A better approach is a timepiece that sets itself, which also eliminates human error. Such clocks have been available for years in Europe, where the shorter distances allow broad coverage for even modest broadcast power.

Fueled by the availability of small inexpensive components, many companies have started manufacturing small freestanding clocks and even wristwatches that use WWVB's signal. Consumers have the choice between digital or analog displays, and AC or battery power. Some models even provide a 1-pulse-per-second output. All of these are made possible by "receiver-on-a-chip" integrated circuits and compact ferrite loop antennas. Even hobbyists routinely "home-brew" their own radio controlled clocks.

Several companies manufacture WWVB receiver calibration systems for users with time and frequency applications that require accuracy and precision. These users, such as 911 emergency call centers, laboratories, and financial markets, desire systems that provide exact, official time stamps. Other users such as police and emergency dispatch centers need precise frequency to maintain tight control of repeater frequencies in mountainous terrain. Master clock systems provide outputs to many displays spanning large areas such as subway platforms, traffic systems, and airports. Hospitals, schools, and office buildings also utilize master clock systems.

2.7 WWVB Measurement Uncertainty

The stable LF radio path used by WWVB makes it possible to transfer frequency with an uncertainty of $< 1 \times 10^{-11}$ when averaged for several hours, and to transfer time with an uncertainty of < 10 microseconds (calibrated for path delay).

3 NIST Radio Stations WWV and WWVH

The world's most famous time announcements undoubtedly are those broadcast by NIST radio stations WWV and WWVH. Millions of listeners are familiar with these broadcasts, where the announcer states the time in hours, minutes, and seconds "at the tone". These stations operate in the part of the radio spectrum properly known as HF (high frequency), but commonly called short wave. WWV is located in Fort Collins, Colorado, sharing the same site as WWVB. WWVH is located in Kauai, Hawaii. Both stations broadcast continuous time and frequency signals on 2.5, 5, 10, and 15 MHz, and WWV also broadcasts on 20 MHz.

WWV and WWVH broadcast the same format on all frequencies, 24 hours a day. A summary of the WWV audio is given in Figure 4. WWVH's audio is similar. At least one frequency should be usable at all times. The most commonly used frequency is 10 MHz, since it is normally usable both during the day and at night. As a general rule, frequencies above 10 MHz work best in the daytime, and the lower frequencies work best at night. The 2.5 MHz broadcasts work best in the area near the station. For example, the 2.5 MHz WWV broadcast should work well for residents of Colorado and its neighboring states, since propagation is similar to that of the commercial AM broadcast band.

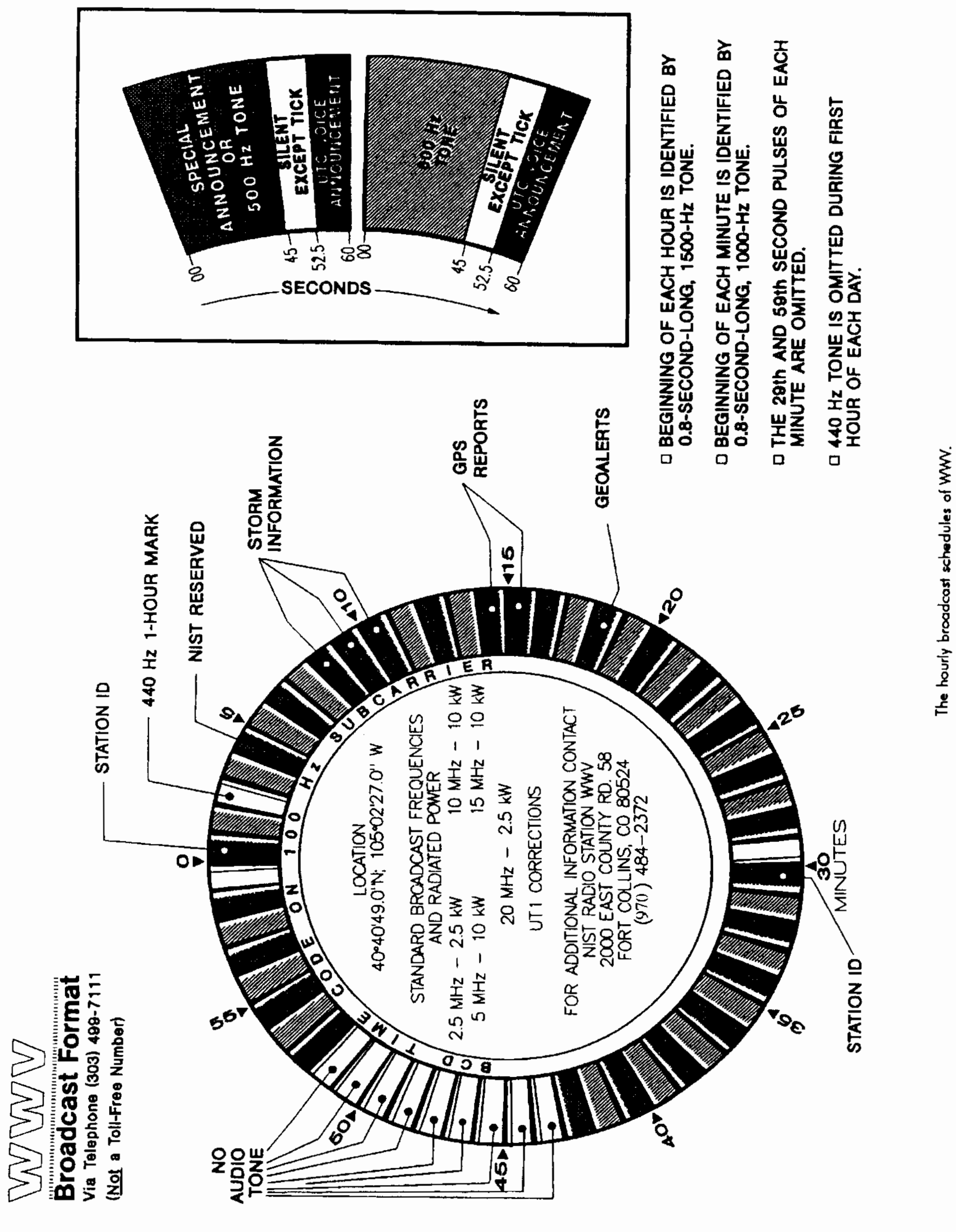


Figure 4

3.1 History of WWV and WWVH

WWV began as an experimental station and its call letters were first announced on October 1, 1919. In the spring of 1920, its first broadcast from Washington, D.C. was music on a frequency of 600 kHz. Later in that year WWV transmitted Department of Agriculture market news and reports on a frequency of 750 kHz. In March 1923, NBS began disseminating standard frequencies from WWV in the range of 200 kHz to 545 kHz and expanded the range of frequencies to cover 75 kHz to 2000 kHz in May 1923.

Through the years many more services have been added. These include the voice announcement of Coordinated Universal Time (UTC), standard audio frequencies, time interval ticks, and standard carrier frequencies. By 1946 WWV was operating on 2.5, 5, 10, 15, 20, 25, 30, and 35 MHz. Today WWV operates on these same frequencies except for 25, 30, and 35 MHz.

The WWV radio station facilities have been relocated several times over the years. They were moved from Washington, D.C. in 1931 to College Park, Maryland (1931-1932), then to Beltsville, Maryland (1932-1943), then to Greenbelt, Maryland (1943-1966). Then in 1966, the facilities were transferred to their current location in Fort Collins, Colorado, which is the same site that WWVB has occupied since 1962.

In November 1948, NIST improved its coverage of the Pacific Basin by adding another HF station on the island of Maui in the territory of Hawaii. This station broadcasts on 2.5, 5, 10, 15, and 20 MHz. WWVH relocated to Kauai, Hawaii in 1971.

3.2 WWV and WWVH Antenna System

The antennas at WWV are simple vertical radiators. Each antenna is fed by a 50–ohm transmission line. The primary transmitters (2.5 through 20 MHz) and the standby transmitters (5, 10 and 15 MHz) all broadcast on vertically polarized, omnidirectional, half-wave dipole antennas (Figure 5). The 2.5 and 20 MHz standby transmitters use vertically polarized, omnidirectional, broadband monopole antennas that are 26 m tall.

Each of the primary transmitters at WWVH feeds an antenna that is a phased array (with the exception of the 2.5 MHz antenna). Like WWV, the radiators are vertical and a quarter-wavelength tall. The WWVH antennas are phased in such a way as to produce a null in the pattern in the direction of WWV. This helps to eliminate interference between the two stations. The backup 2.5 MHz antenna is a quarter-wave length vertically polarized, omnidirectional, broadband monopole. The back-up antennas for 5, 10, and 15 MHz are vertically polarized, omnidirectional, monopole fiberglass whips.

3.3 WWV and WWVH Transmitters

There are two types of WWV transmitters. The first type is a plate-modulated class C transmitter with approximately 50% efficiency. Each transmitter for 5, 10 and 15 MHz produces 10 kW. The other type of transmitter is a class A with an efficiency of approximately 20%. These transmitters for 2.5 and 20 MHz produce 2.5 kW each.

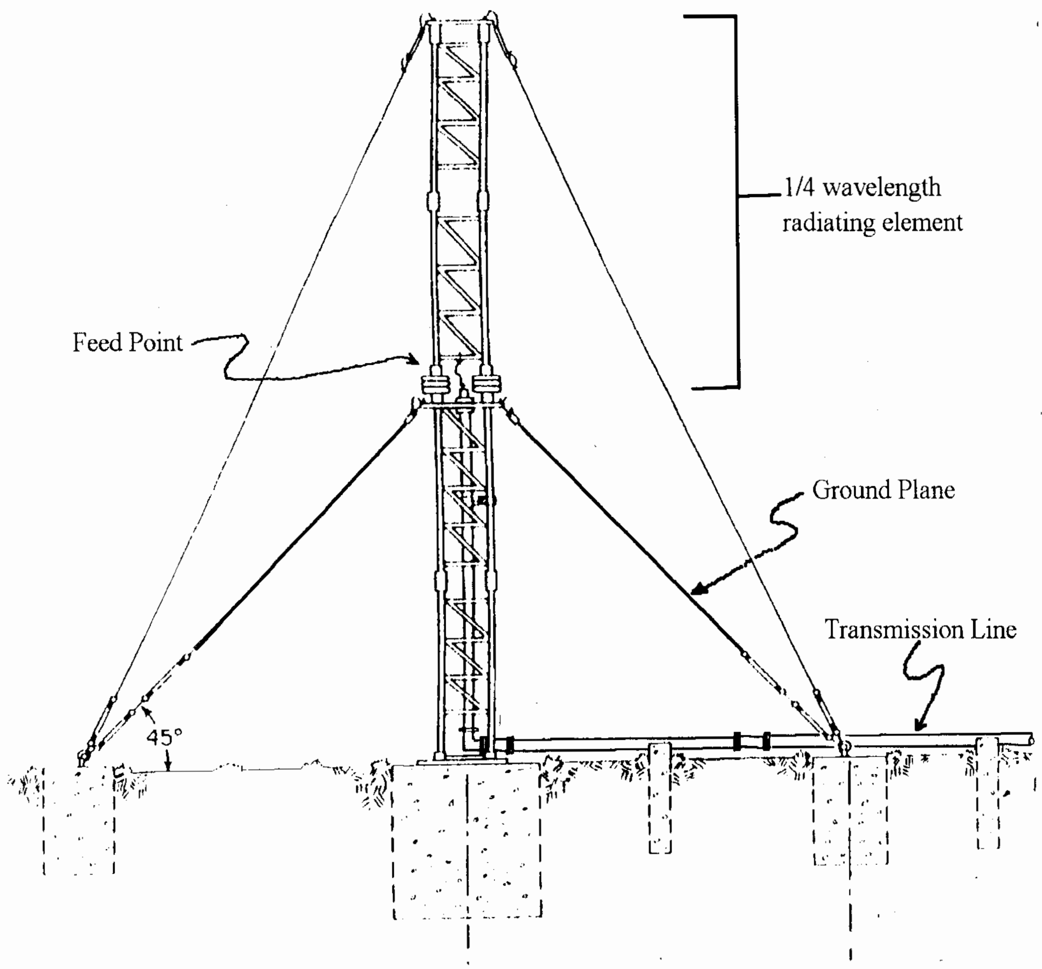


Figure 5

All frequencies have a dedicated standby transmitter that will automatically begin operating within three minutes of a primary system failure. These standby transmitters are all class A. At 5, 10, and 15 MHz they produce 3 kW. At 2.5 and 20 MHz they have an output of 2.5 kW.

WWVH uses plate-modulated class C transmitters on 5, 10, and 15 MHz that produce 10 kW with 50% efficiency. The 2.5 MHz transmitter is a class A and has an output of 5 kW with 20% efficiency. All four frequencies have a backup transmitter system that automatically begins transmitting within three minutes after the primary system fails. All four of the backup transmitters are 5 kW class A, identical to the primary transmitter on 2.5 MHz.

3.4 WWV AND WWVH PROPAGATION

The time and frequency signals broadcast from the HF station travel by sky wave. The benefit of this is that the transmission can be returned to the earth by the ionosphere, and then reflected off the earth, and then returned again to the earth by the ionosphere. These "hops" by the electromagnetic energy can make the signal available virtually worldwide. Reception reports have been received from many parts of the world including the South Pole. The distance over which these signals travel is affected primarily by the state of the ionosphere, the main factors being the time of day and solar activity. As a general rule of thumb, reception of the frequencies below 10 MHz is favored at night and reception of those above 10 MHz is favored during day. During the peak of a solar cycle (occurring every 11 years, the most recent in 2001) the reception of frequencies above 10 MHz is greatly improved.

3.5 WWV AND WWVH MEASUREMENT UNCERTAINTY

The variability of the HF radio path makes the received uncertainty of WWV and WWVH much larger than that of WWVB. Frequency can still be transferred with an uncertainty of < 1×10^{-7} (parts in 10^9 are possible if one averages for several hours), and time can be transferred with an uncertainty of < 1 microseconds (calibrated for path delay).

4 HOW NIST CONTROLS THE TRANSMITTED FREQUENCIES

NIST maintains several cesium and rubidium frequency standards at both the Colorado and Hawaii station sites. These frequency standards are steered to the same rate as UTC and serve as the source for all of the timing and frequency standards that are transmitted from the stations. (Figure 6) WWVB and WWV both use the same reference oscillators at the Colorado location.

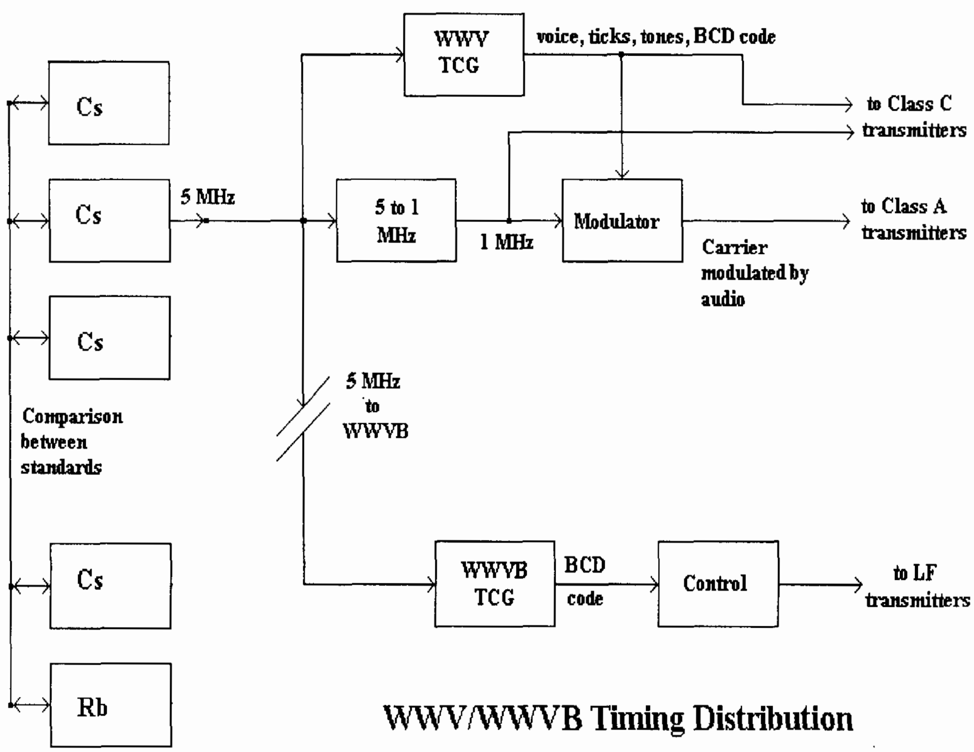


Figure 6

4.1 Agreement with UTC(NIST) Time Scale

UTC(NIST), the time scale that serves as a national standard for time and frequency, is located in NIST's laboratories in Boulder, Colorado. It consists of a primary cesium fountain standard (designed and built at NIST) called NIST-F1, and an ensemble of commercial cesium beam and hydrogen maser frequency standards. UTC(NIST) is maintained within parts in 10^{14} in frequency to the international UTC time scale maintained by the Bureau International des Poids et Mesures (BIPM) in France.

The frequency standards located at the station sites are steered to agree with UTC(NIST), and therefore provide traceability to the national standard. The transmitted frequencies are controlled to within parts in 10^{13}, and time is kept to within a few hundred nanoseconds. Radio propagation noise, as seen earlier, makes the received uncertainties larger than the transmitted uncertainties.

4.2 Control of WWV and WWVH

The standards at WWV and WWVH are compared daily to the time scale maintained at the NIST laboratories in Boulder, Colorado. This comparison is made by a method known as "GPS common view." This is done by comparing the 1 pulse-per-second (pps) outputs from the standards at the radio stations to a 1 pps output generated by a Global Positioning System (GPS) satellite receiver as it tracks a GPS satellite. The same satellite is tracked in Boulder at the same time and the 1 pps output of that receiver is compared to the NIST time scale. Staff members at the radio stations retrieve this time difference data from a data logger in Boulder and compare it with the station data. From this, the difference between the UTC(NIST) and the station standards can be determined to within 50 nanoseconds and subsequently, the 5 MHz signal from the cesium standard can be steered. During the interval between common view comparisons, the cesium and rubidium standards are monitored and compared with each other to detect any sudden changes in frequency.

The 5 MHz output from the steered cesium standard is then sent to a time code generator (TCG). In that TCG the standard audio frequencies 440, 500 and 600 Hz are derived from the 5 MHz reference. Also produced are the ticks that mark the standard one-second time interval, and a 100 Hz BCD time code in an IRIG-H format. (Figure 7)

Also derived from the 5 MHz output is a 1 MHz signal that is used to generate the carrier frequencies on which the time signals are conveyed to the user. The carriers are modulated with the audio information and amplified by the transmitter for broadcast.

4.3 Control of WWVB

WWVB receives its frequency reference from the same bank of cesium and rubidium frequency standards kept at WWV. The 5 MHz signal from the cesium standard is sent directly to the TCG at WWVB. A 60 kHz carrier is derived from the 5 MHz reference and this carrier is modulated with BCD time code. (Figure 8) This time code is then sent to the transmitter for amplification and broadcast.

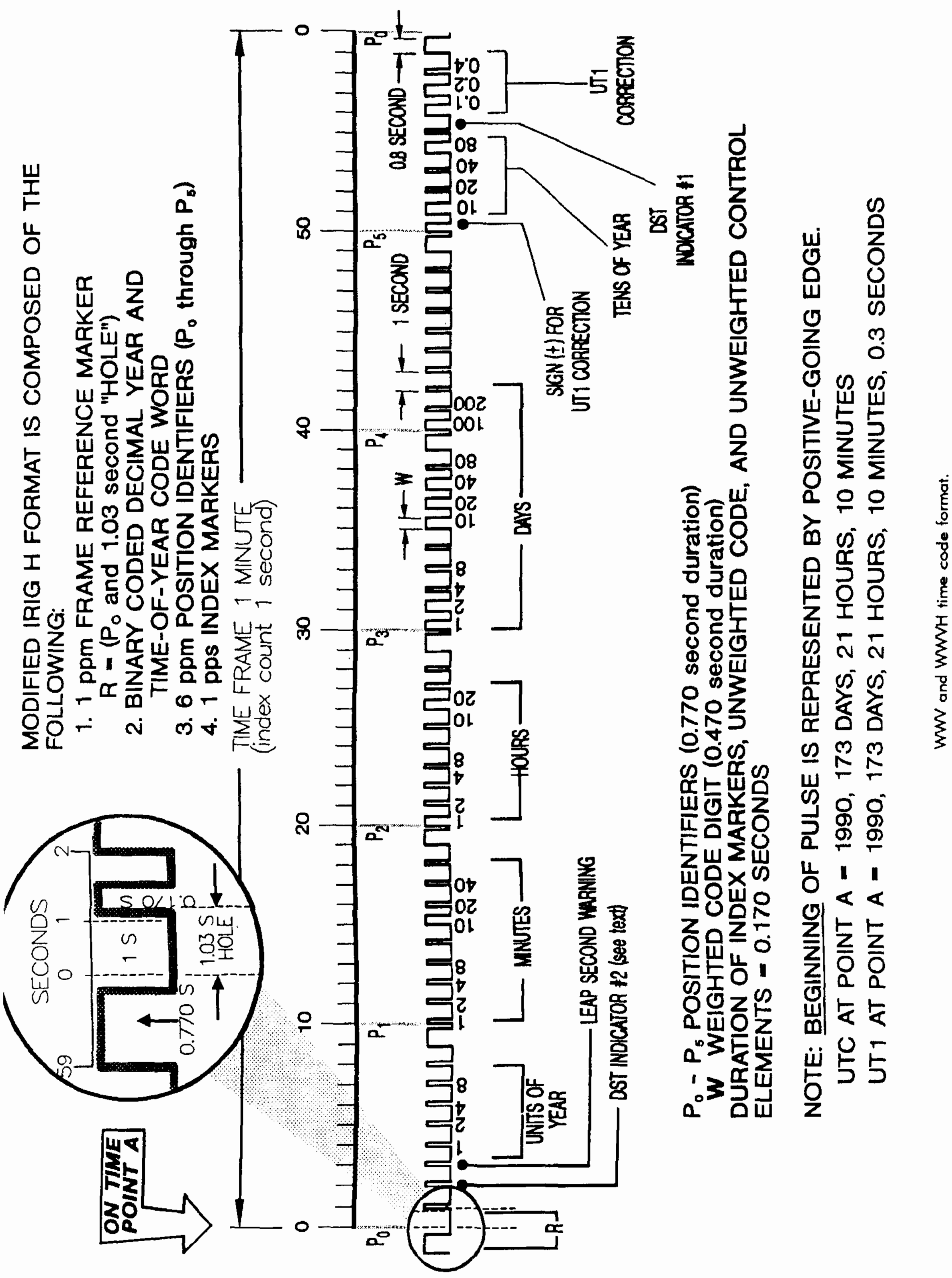
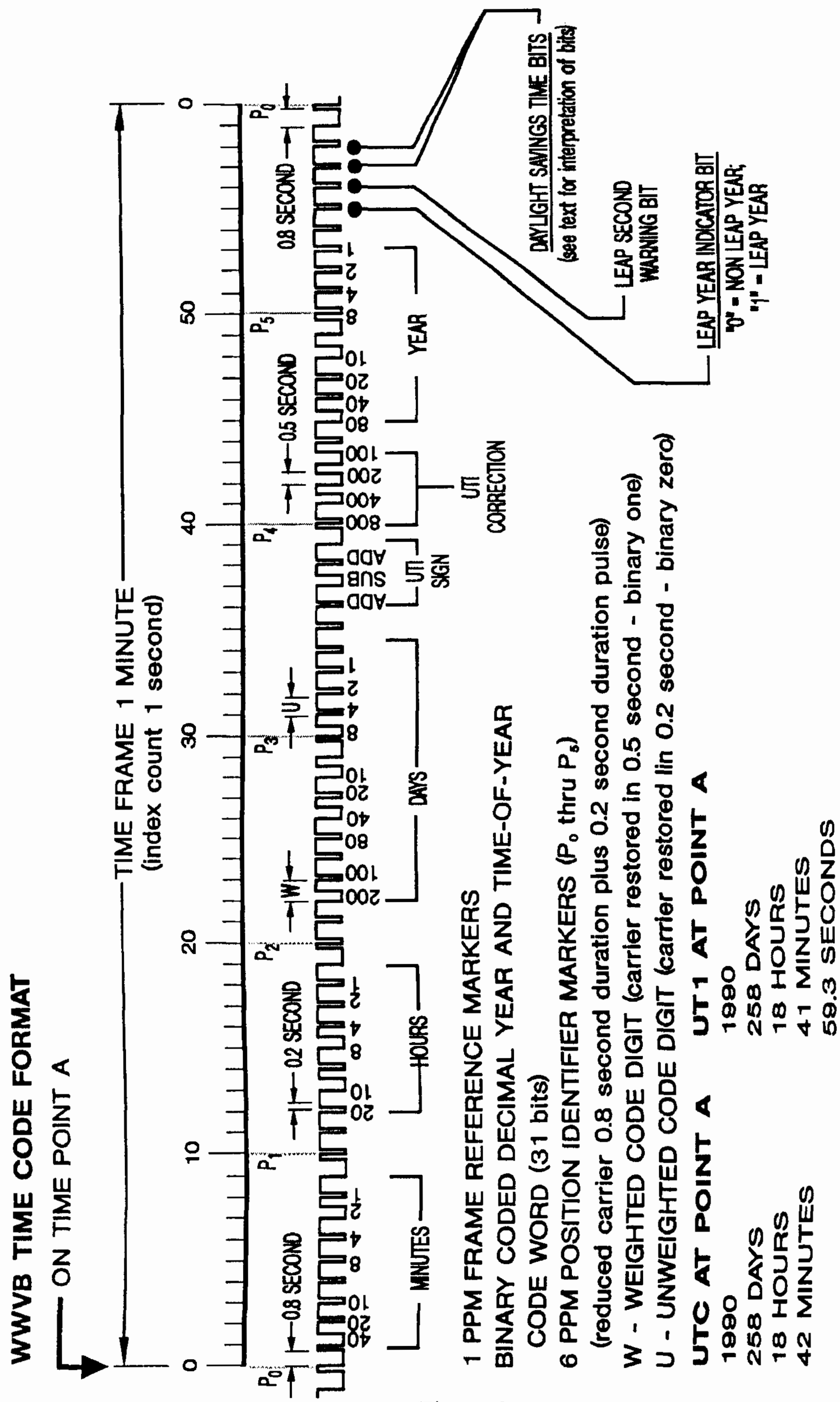

MODIFIED IRIG H FORMAT IS COMPOSED OF THE FOLLOWING:
1. 1 ppm FRAME REFERENCE MARKER R = (P_0 and 1.03 second "HOLE")
2. BINARY CODED DECIMAL YEAR AND TIME-OF-YEAR CODE WORD
3. 6 ppm POSITION IDENTIFIERS (P_0 through P_5)
4. 1 pps INDEX MARKERS
ON TIME POINT A
SECONDS
59
0
1
2
1 S
0.770 S
0.170 S
1.03 S HOLE
TIME FRAME 1 MINUTE (index count 1 second)
0
10
20
30
40
50
0
P_0
P_1
P_2
P_3
P_4
P_5
P_0
W
1 SECOND
0.8 SECOND
R
UNITS OF YEAR
MINUTES
HOURS
DAYS
LEAP SECOND WARNING
DST INDICATOR #2 (see text)
SIGN (±) FOR UT1 CORRECTION
TENS OF YEAR
DST INDICATOR #1
UT1 CORRECTION
P_0 - P_5 POSITION IDENTIFIERS (0.770 second duration)
W WEIGHTED CODE DIGIT (0.470 second duration)
DURATION OF INDEX MARKERS, UNWEIGHTED CODE, AND UNWEIGHTED CONTROL ELEMENTS = 0.170 SECONDS
NOTE: BEGINNING OF PULSE IS REPRESENTED BY POSITIVE-GOING EDGE.
UTC AT POINT A = 1990, 173 DAYS, 21 HOURS, 10 MINUTES
UT1 AT POINT A = 1990, 173 DAYS, 21 HOURS, 10 MINUTES, 0.3 SECONDS
WWV and WWVH time code format.

Figure 7



WWVB time code format.

Figure 8

5 SUMMARY

Radio broadcasts of time and frequency, now nearly 100 years old, will continue with new vigor into this century. After 35 years of operation, NIST radio station WWVB has recently undergone a thorough redesign and rebuilding of its transmitter facilities that will increase and maintain its usefulness and availability to the public for years to come. Ongoing improvements to all three stations, WWVB, WWV, and WWVH, will ensure dependable service for years to come. These improvements assure continuity and reliability of these heavily used signals. The demand for these broadcasts continues to grow as users create new and innovative ways to use these radio signals. Manufacturers continue to create new, lower cost products, all in an effort to place "Atomic Time" in every home and office.

More information about WWVB, WWV, and WWVH can be found at the NIST Time and Frequency Division web site at http://www.boulder.nist.gov/timefreq.

6 REFERENCES

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