WWVB IMPROVEMENTS:

New Power from an Old Timer

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Abstract

In response to advancements in receivers and increased emphasis of traceability of frequency to the national standard, the time-and-frequency radio station, WWVB, of the National Institute of Standards and Technology (NIST) recently underwent numerous improvements, including a 7 dB boost in radiated power, resulting in significantly greater signal availability throughout North America. This paper describes the history of WWVB, the improvements recently made to the station, theoretical coverage, and consumer-oriented receivers projected to number in the millions of units in the next few years.

1 INTRODUCTION

1.1 HISTORY OF VLF/LF IN TIME AND FREQUENCY BROADCASTS

The U.S. Naval Observatory broke new ground in 1904 when it broadcast an experimental time transmission from the city of Boston as an aid to navigation. Soon it was recognized that large areas could be covered and that navigation would benefit from accurate broadcasts of time and frequency at very low and low frequencies (VLF/LF). Other applications were developed as well. For example, as the airwaves became more crowded a means was needed to calibrate radio equipment. WWV, a high-frequency (HF) station that currently coexists at the WWVB site, started out as an LF station in 1923. It broadcast standard "wave" signals to the public on frequencies ranging from 75-2000 kHz.

Since about 1960 the Navy has used its VLF stations for transmitting precise frequencies.

Another source of time and frequency was the Omega Navigation system, which just recently ceased operation. It transmitted accurate navigation signals around 10 kHz. At this low frequency, changes in phase are easily noted and position can be determined to a high degree of accuracy. The long-range navigation (LORAN) system, which began development during WWII, operates around 100 kHz. By having stable and accurate LORAN transmissions, ships and aircraft can find their position with excellent accuracy. LORAN is also used as a frequency reference.

1.2 FREQUENCY ALLOCATION IN ITU REGIONS 1, 2, AND 3

The International Telecommunication Union (ITU), which is an agency of the United Nations, has divided the globe into three regions. (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. VLF and LF time and frequency broadcasts 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.

1.3 PROPAGATION CHARACTERISTICS

The propagation of VLF/LF electromagnetic energy has many properties that make VLF/LF well suited for time and frequency transfer. At these longer wavelengths, losses in the earth's surface are low. Thus, the ground wave can travel well for thousands of kilometers and moderate amounts of power can cover large portions of a hemisphere. Other advantages are stable path, low attenuation by the atmosphere, and reliability during ionospheric disturbances. These characteristics make it possible to transfer frequency with an uncertainty of $< 1 \times 10^{-11}$, and to transfer time with an uncertainty of < 100 us (calibrated for path delay.)

1.4 EXISTING STATIONS

Numerous stations worldwide are broadcasting time and frequency standards via VLF/LF and more are planned. Many of these stations are designated as navigation systems. Some, such as WWVB, are used to distribute the standard second to the public.

2 WWVB BEFORE UPGRADE

2.1 HISTORY OF WWVB AND WWVL

The first standard frequency broadcast of 60 kHz started in July 1956, from Station KK2XEI. This 2 kW transmitter (located at the National Bureau of Standards (NBS) in Boulder, Colorado) 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 small.

NBS (currently NIST) also began an experimental VLF standard frequency broadcast from a valley span antenna at Sunset, Colorado, just northwest of Boulder in April 1960. This signal, though less than 15 watts, 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 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 watt standard 20 kHz signal in August 1963.

On July 1, 1965, WWVB added a time code to its broadcast. This time code is sent in binary-coded decimal (BCD) format. Bits are sent by shifting the power of the carrier. 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, WWVL transmissions were ended and WWVL was no longer in service. WWVB continued to broadcast its time code, but its equipment was aging and lacked good documentation.

2.2 Description of WWVB and WWVL antenna systems

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 consisted of four 122-m masts arranged in a diamond shape. (Figure 2) Suspended between the four towers was a system of heavy cables, often called a capacitance hat or top hat. This top hat was electrically isolated from the towers, and it was electrically connected to a downlead that was suspended from the center of the top hat. The downlead was the radiating element.

Ideally, to have an efficient radiating system, the radiating element needs to be at least a one-quarter wavelength long. At 60 kHz, where the wavelength is nearly 5000 m, it is impossible to have the desired one-quarter wavelength antenna since it would 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 were still only a fraction of the transmitted wavelength, and were inherently capacitive and had a small radiation resistance.

The downlead of each antenna was terminated at its own helix house under the top hats. The helix houses each contained a large inductor to cancel the capacitance of the short antenna and a variometer (variable inductor) to tune the antenna system during periods when snow or wind loaded the antenna.

Energy was fed from the transmitters to the helix houses on a 500 ohm open-air balanced transmission line that ran approximately 435 m to each house. The many utility poles that held up the transmission lines became cracked and damaged over the years.

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. However, it rarely saw any service.

2.3 Description of WWVB transmitters

Not much is known about the origins of the two transmitters that carried the WWVB broadcast for so long. They were nicknamed “Blue” and “Gray” in reference to their color. They are thought to be WWII era HF transmitters that were highly modified. Gray served as the primary transmitter and Blue served as the backup. Either could be switched into the 500 ohm balanced feed line that ran to the helix house where it was matched to the antenna.

2.4 Performance evaluation

Except for the occasional equipment fault, WWVB broadcast for many decades without significant interruption in service. Enough redundancy was built in so that backup systems could restore the time code signal until an electronics technician could respond to the original problem.
One significant problem was that the WWVB antenna was subject to icing, which could occur once or twice

each winter. Most icing "events" were inconvenient but short-lived. When conditions were right, frost would form around 4 or 5 am and be gone by 8 or 9 am as the sun came out and the temperature rose. Radiated power would drop due to resistive losses across frost-covered insulators and the variometer would approach it tuning limit as the ice distorted the antenna.

On the morning of February 7, 1994, a heavy mist froze to the antenna and the temperature dropped below freezing for two days. The variometer reached its tuning limit and the broadcast was interrupted. For approximately 30 hours the broadcast was off, becoming an inconvenience for users across North America. Brainstorming about solutions to the icing problem made it apparent that any quick fixes would be too expensive for what would be gained. The entire WWVB system needed to be rethought.

Before an adequate solution could be found, it would be beneficial to start with baseline measurements to determine which areas would benefit most from improvements. The Naval Command, Control and Ocean Surveillance Center Research, Development, Test and Evaluation Division (NraD) and the Pacific Sierra Research Corporation (PSR) accomplished this in October 1994. The antenna measurements are summarized in Table 1. A model of the antennas is shown in Figure 3.

One of the positive findings in the report was that the arid Colorado climate has protected the overall antenna system well. Another result of the measurements was the proposition that using the WWVB and the WWVL antennas in parallel could increase the efficiency of the entire system.

3 ENGINEERING STUDIES

3.1 A NEW STATION IS ENVISIONED

In November 1996, PSR submitted an engineering plan to NIST that laid out the overall concept of how WWVB could be modified to negate the effects of icing, improve reliability, and increase the radiated signal power by at least 6 dB. The plan suggested replacing Blue and Gray with three more powerful, modern transmitters; replacing the open balanced transmission line with a buried 8 cm diameter 50 ohm semi-ridged coaxial cable; and replacing the helix and variometer in the helix house with a variometer having a greater tuning range.

3.2 THE SEARCH FOR NEW HARDWARE

Every effort was made to seek out affordable, high quality parts and equipment for the entire system. It was difficult to find "off the shelf" LF parts. Insulators had to be ordered and many parts had to be handmade. Nearly one kilometer of 50 ohm coaxial cable was purchased and installed in trenches to the helix houses. Some old vacuum tube equipment was also replaced with new solid-state components.

3.3 EQUIPMENT RECYCLED

When new equipment could not be purchased or fabricated it was acquired from surplus. Careful searching, good communication and cooperation with other departments at the highest levels made acquisition of surplus equipment possible. The late Secretary of Commerce Ron Brown petitioned John Dalton, the Secretary of the Navy, for three FRT-72 transmitters that were available from Navy operations in Virginia, Scotland, and Iceland. Two variometers with extended tuning capability came from the decommissioned Navy LF station NSS in Annapolis, Maryland. Several trips were made to La Moure, North Dakota, by NIST staff to obtain Litz wire and other components that would be used in the WWVB helix houses. One of the largest contributions of recycled equipment came from the old WWVL system, which had been virtually unused for

25 years. The WWVL antenna would make it possible to continue the WWVB broadcast uninterrupted as the WWVB antenna system was rebuilt and later would make the more efficient dual antenna system possible.

One of the greatest challenges was to build the new WWVB system while keeping both the current WWVB and the HF station WWV operational. This would have to be done with the current staff at the station, a minimum of contractors, and some staff from the Boulder NIST Time and Frequency Division when they could be spared from their own duties. Also, during this time, fewer standby options would be available during construction in the helix houses or on one of the antenna systems.

4 THE WWVB UPGRADE AND FINAL SYSTEM

The upgrade to the WWVB system went through several phases over the six years it took to complete. The first realistic short-term goal was to improve the radiated power by 4 dB. This could be done quickly by matching one antenna and one 50 kW transmitter, then using the transmitter it had replaced as a standby. This 4 dB increase of radiated power was achieved on December 19, 1997. This provided users with greater signal strength until the south helix house could be rebuilt and two more FRT-72 transmitters installed. Also, the means to combine the north and south systems needed to be completed. The second increase of 3 dB was completed on August 5, 1999.

4.1 SCHEMATIC OF NEW SYSTEM

The final configuration of the WWVB system consists of one FRT-72 transmitter delivering an amplified time code signal into the north antenna system, and one FRT-72 transmitter feeding the south antenna system. (Figures 4 and 5) The low-level time code is fed to the console where it is passed through a control system and then delivered to the two operating transmitters. The matrix controls the system by providing the operator's selections at the matrix to a programmable logic controller (PLC).

4.2 DESCRIPTION OF TRANSMITTERS

There are a total of three FRT-72 transmitters at the WWVB site. Two are in constant operation and one serves as a standby. Each FRT-72 transmitter consists of two identical power amplifiers (PA), which are combined to produce the greatly amplified signal sent to the antenna. (Figure 6) Each of the two power amplifiers 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-watt drive signal to the grids of the FRT-72 PA tubes, which are biased as class AB amplifiers.

4.3 DESCRIPTION OF ANTENNA SYSTEMS

Probably the most radical change to the WWVB system occurred in the antenna systems. As mentioned earlier, the arid Colorado climate inflicted little aging on the antenna. All antenna parts that were sound were cleaned and inspected. When new or higher quality materials were available, deteriorating items were replaced. The antennas were fitted with new high voltage insulators; also, both downleads are now steel core aluminum cable. All electrical and mechanical connections were inspected and cleaned and broken parts were replaced.

The helix houses were gutted and refitted with the surplus variometers, loading coil, and RF switches that could enable the station to switch from one to two antenna operation. Between the helix houses fill dirt was brought in, compacted and trenched, and the trenches were lined with concrete. For greater protection, the new 50 ohm coaxial cable along with all new control and power cables were laid in the trench.

A matrix was installed to enable an operator to select which transmitter will go into a particular antenna or dummy load. Automatic tuning was added to provide a dynamic match between the transmitter and the antenna system during icy and/or windy conditions. When operating in "single" mode, the PLC looks for a phase difference between voltage and current at the PA. If one is detected, an error signal is sent to a 3-phase motor in the helix house that rotates the rotor inside the variometer. This retunes the antenna and restores the match between the antenna and transmitter. While operating in dual mode (one transmitter in each antenna) one transmitter acts as the master and the other is the slave. The difference in phase between voltage and current at the PA is sensed at only one transmitter, but is used to tune both antennas.

4.4 THEORETICAL EFFICIENCY OF SYSTEM

An advantage at low frequencies, such as 60 kHz, is that even low power signals propagate well. As mentioned in section 2.2, a disadvantage of an antenna system for these low frequencies is that its physical length is much less than a quarter wavelength. As the length of a vertical radiator becomes shorter compared to wavelength, the radiation resistance falls quickly and the ratio of radiation resistance (R_{rad}) to gross resistance ($R_{gross} = R_{rad}$ + resistance due to losses) becomes small. 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 had an efficiency of 57.5% (R_{gross}=0.80 ohms, R_{rad}=0.46 ohms.)

The first phase of the upgrade (completed in December 1997) permitted the use of one FRT-72 to the north antenna system. A forward power of 50 kW produced a radiated power of about 25 kW. One advantage of transmitting from each antenna is that the combined system produces a total efficiency of 65%. Now with a forward power from each transmitter of only 38 kW, the combination of the two transmitting systems will produce a radiated power of 50 kW.

4.5 WWVB COVERAGE

One benefit of the dual antenna operation is that there is a 1 dB increase of power in the east to west direction over that of an omni-directional pattern due to the antenna pattern "lobes" created by this phased array. NRaD has also created computer models that predict signal strength. (Figures 7-10) Note that the coverage area is much larger at night. Signal strength charts in dB above one microvolt per meter were also generated. (Figures 11-14) Also, the Y axis of these figures can be stated in microvolts per meter, where 10db equals 3.2uv/m, 20db equals 10uv/m, 30db equals 32uv/m, 40db equals 100uv/m, etc.

5 SUMMARY

Radio broadcasts of time and frequency, now nearly 100 years old, will continue with new vigor into the next century. After 35 years of operation, NIST radio station WWVB has undergone a thorough redesign and rebuilding of its transmitter facilities that will increase its usefulness and availability to the public for years to come. Through the efforts of many people, WWVB has acquired and installed high quality U.S. Navy transmitters and variometers. The former WWVL 20 kHz antenna system was also returned to full-time operation as part of WWVB. These improvements enable NIST to provide dependable time and frequency dissemination even in inclement weather. The demand for this service is constantly growing as 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 and its time code can be found at the NIST Time and Frequency web site: http://www.boulder.nist.gov/timefreq.

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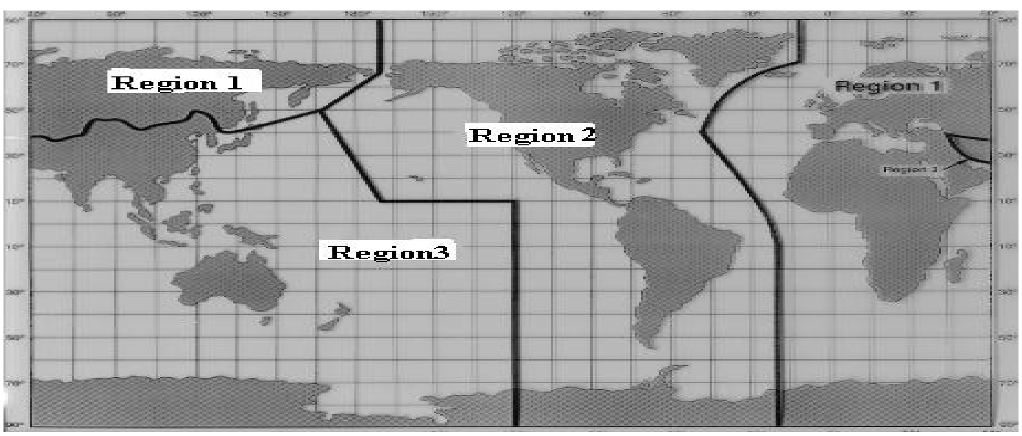

Figure 1 Map of ITU Regions

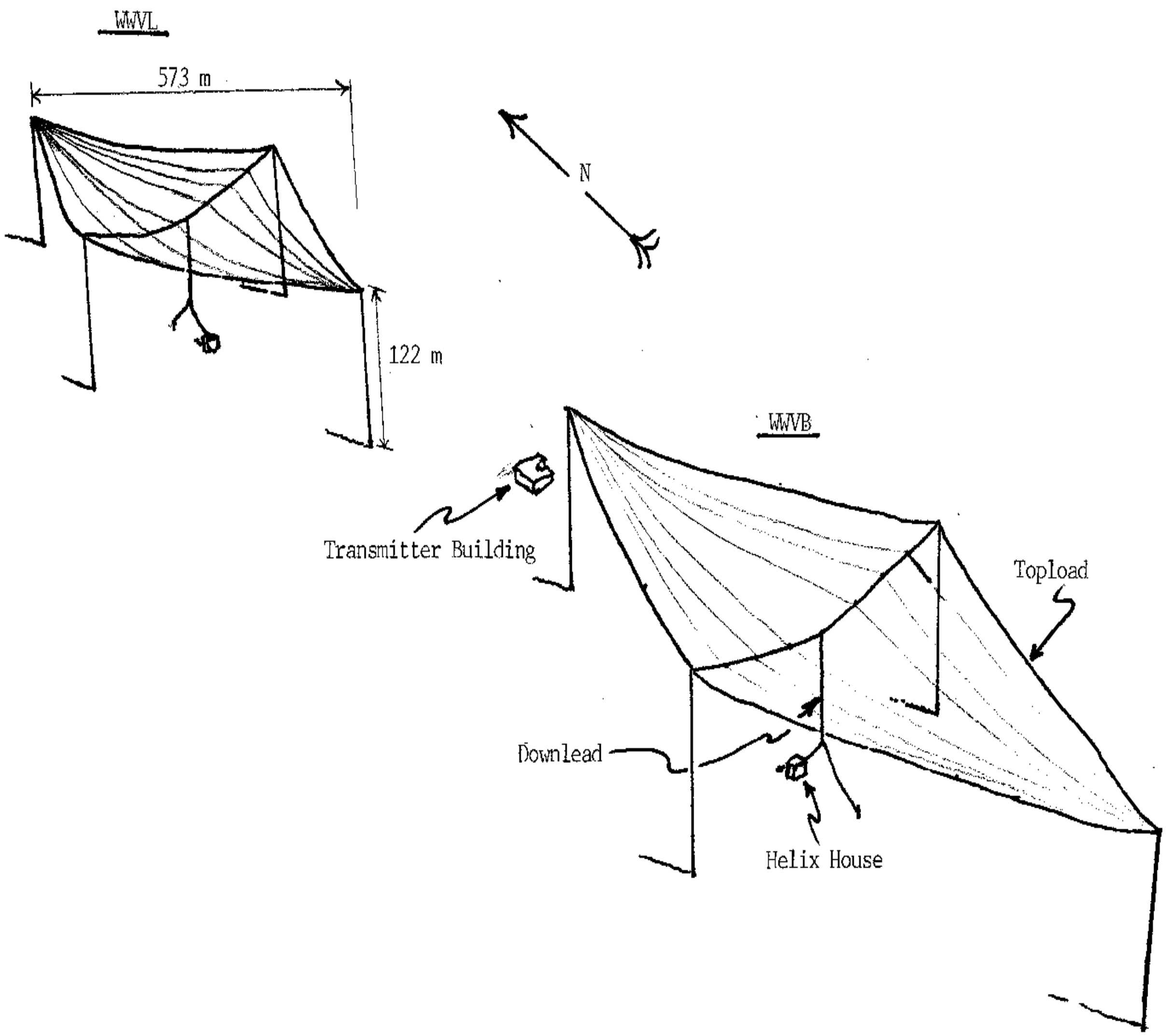

Figure 2 WWVB and WWVL Antenna Systems

Shunt Capacitance (Cs) = 1.06 nF (south), 1.00 nF (north)
Downlead Inductance (Id) = 208.8 uH (s), 208 uH (n)
Toplaod Capacitance (Ct) = 13.6 nF (both antennas)
Antenna Resistance (Ra) = 0.80 ohms (s), 0.91 ohms (n)

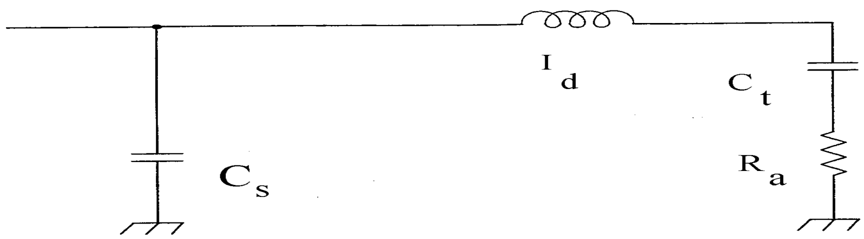

Figure 3
Antenna model and component values for WWVB and WWVL.

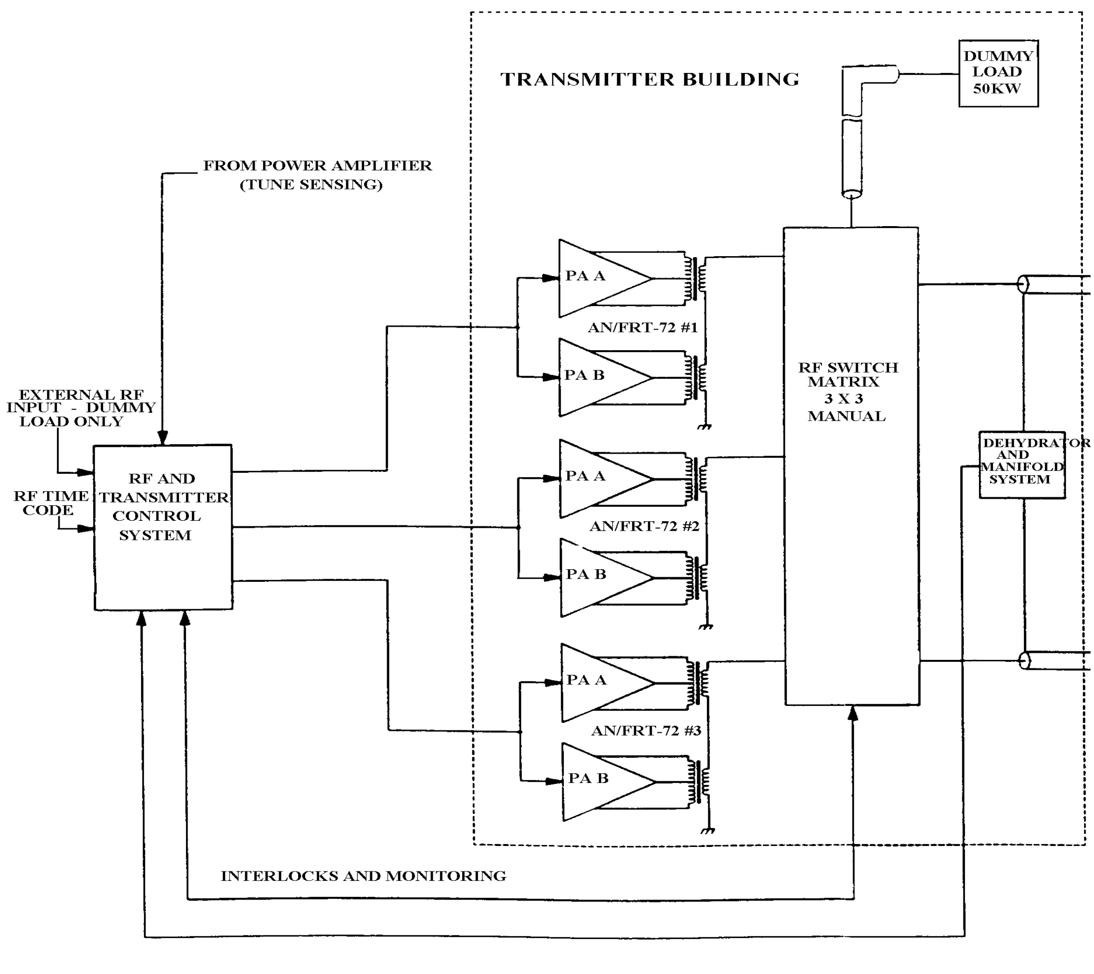

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Figure 4
Block diagram of WWVB transmitter room.

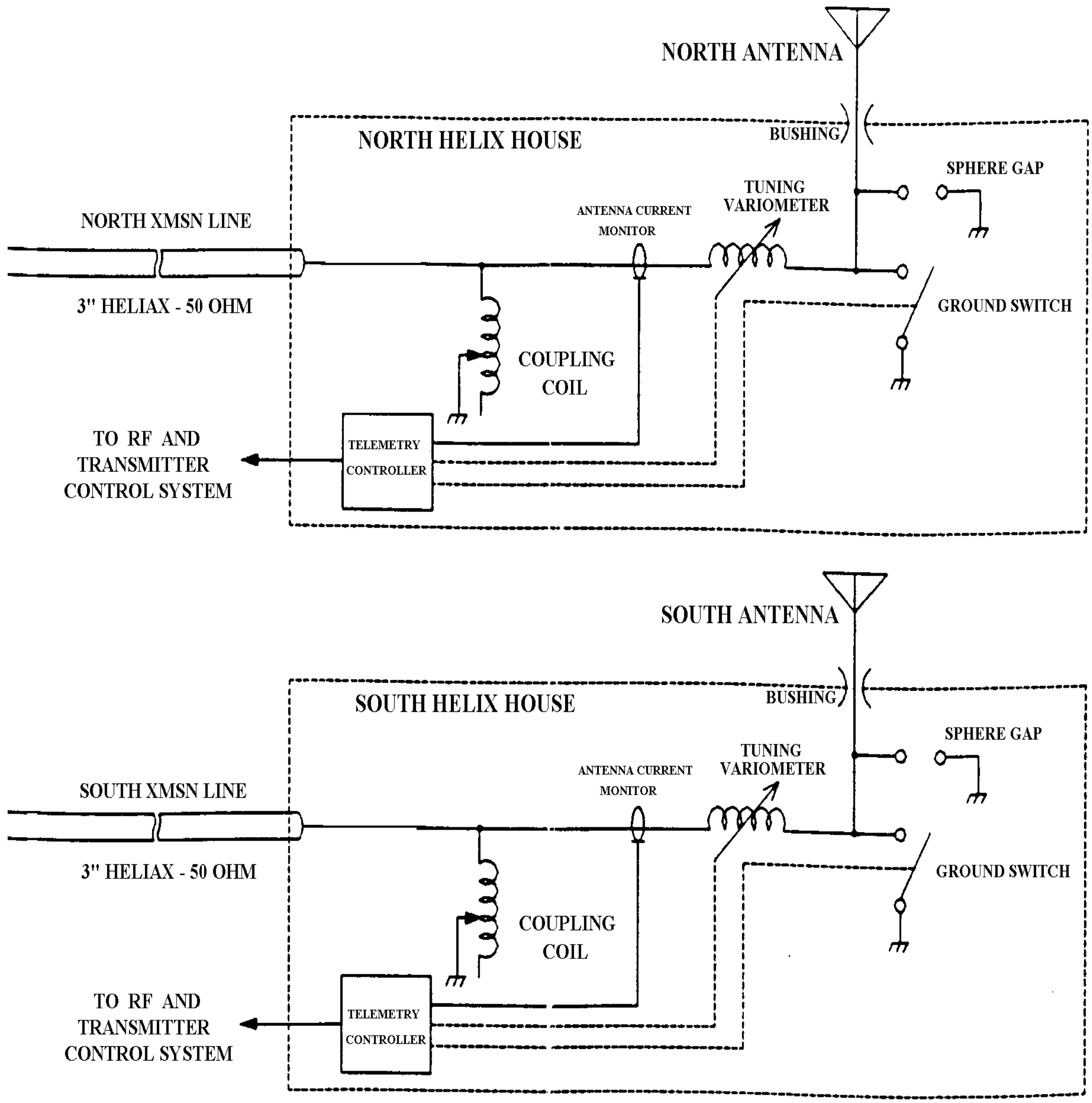

Figure 5
Block diagram of WWVB helix houses.

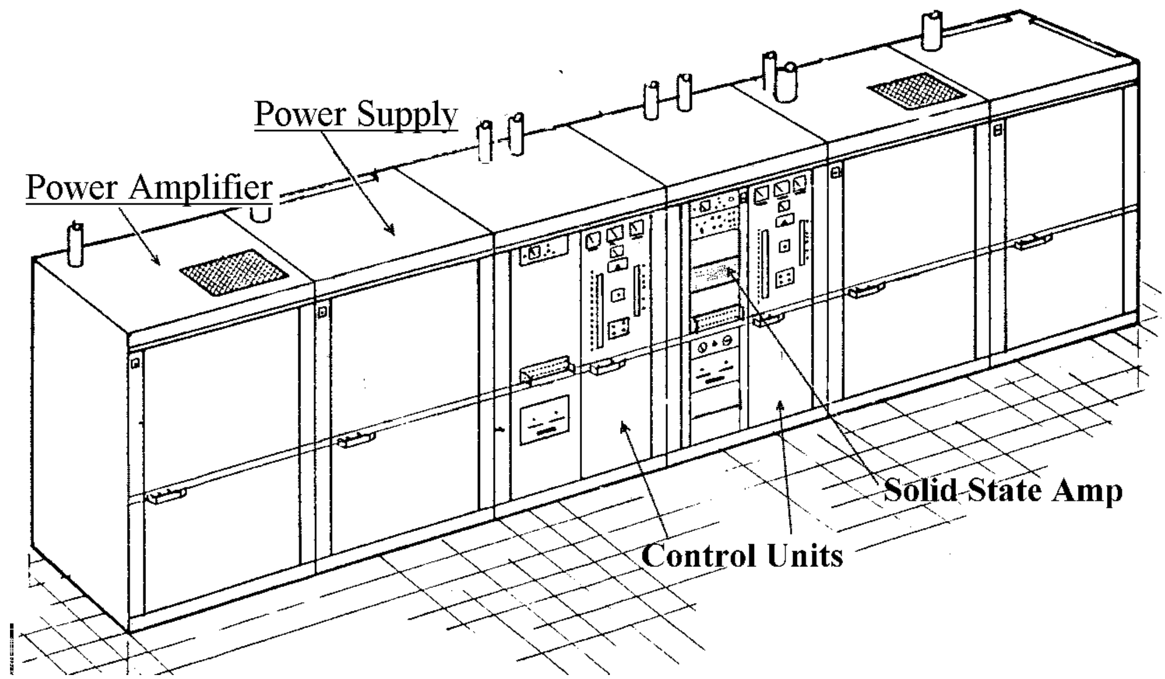

Figure 6
Diagram of FRT-72

60 kHz Parameters	South Antenna	North Antenna
Radiation Resistance (Ohms)	0.46	0.46
Antenna Gross Resistance (Ohms)	0.80	0.91
Antenna Radiation Efficiency	57.5%	50.6%
Antenna Base Reactance (Ohms)	-114.9	-112.9
Antenna Downlead Inductance (microheneries)	208.8	208.0

Table 1
Measured antenna parameters at 60 kHz for both the north (WWVL) and south (WWVB) antennas.

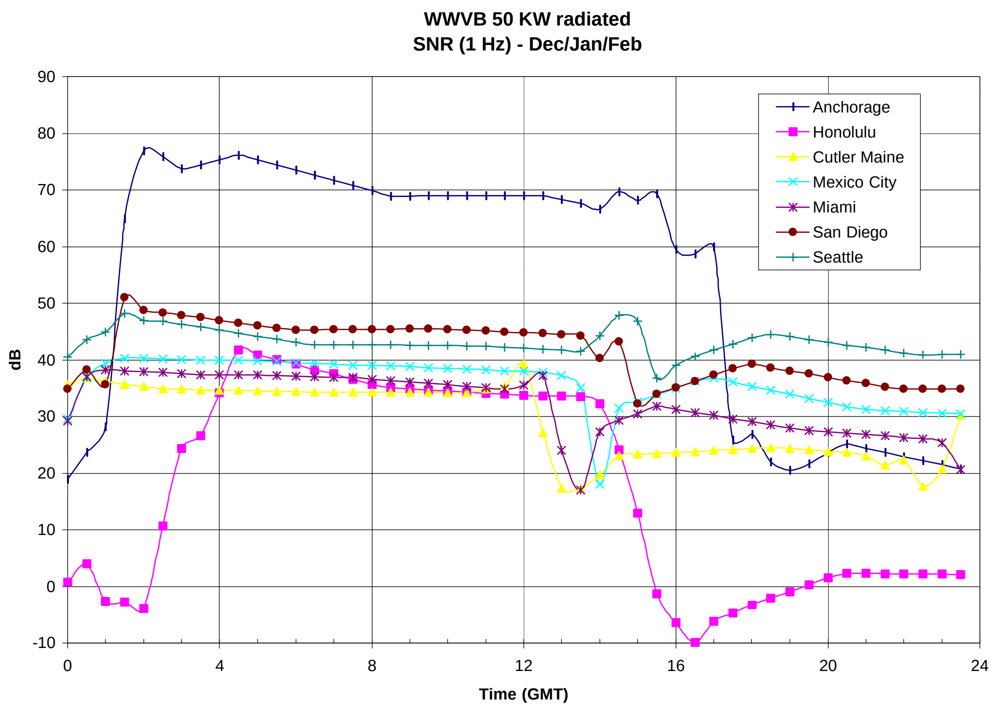

Figure 7 - Signal to noise ratio with 1 Hz Bandwidth during the winter months.

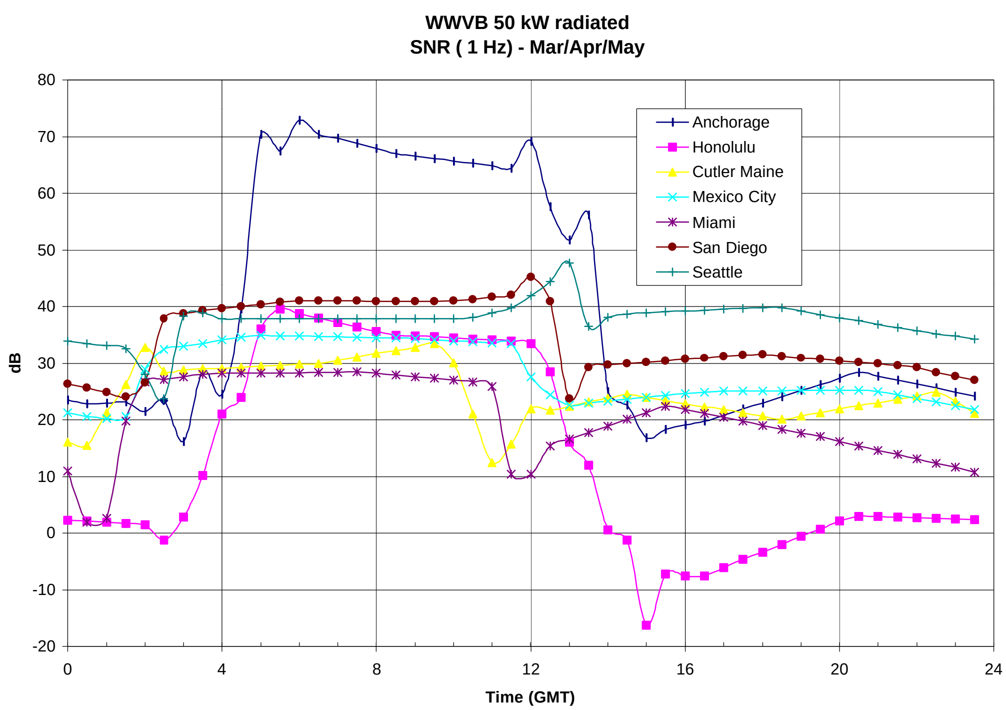

Figure 8 - Signal to noise ratio with 1 Hz Bandwidth during the spring months.

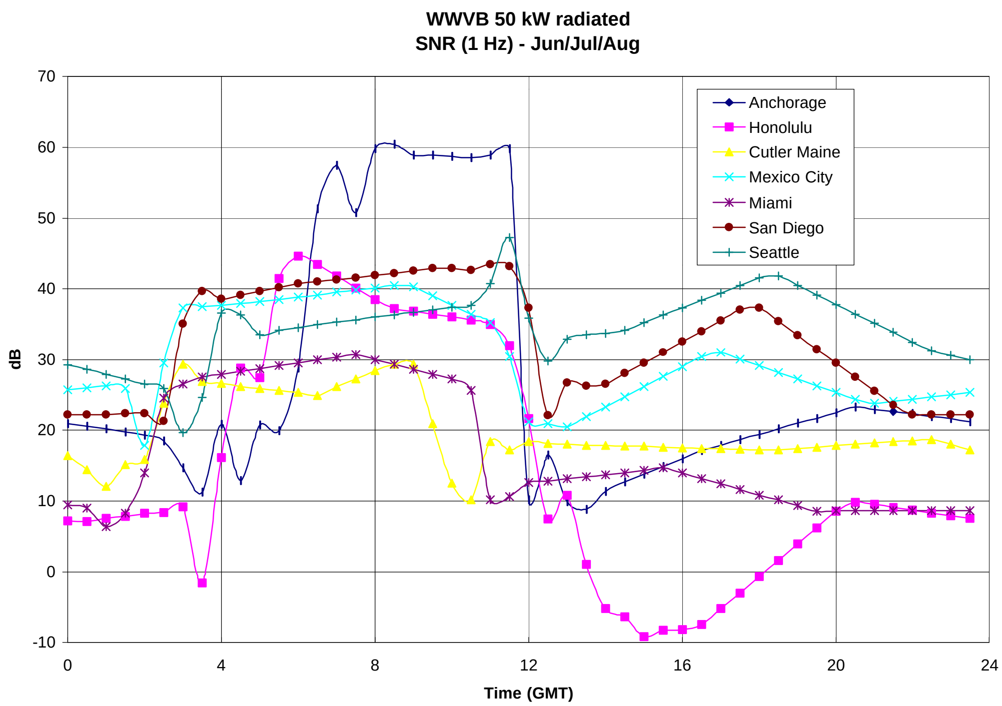

Figure 9 - Signal to noise ratio with 1 Hz Bandwidth during the summer months.

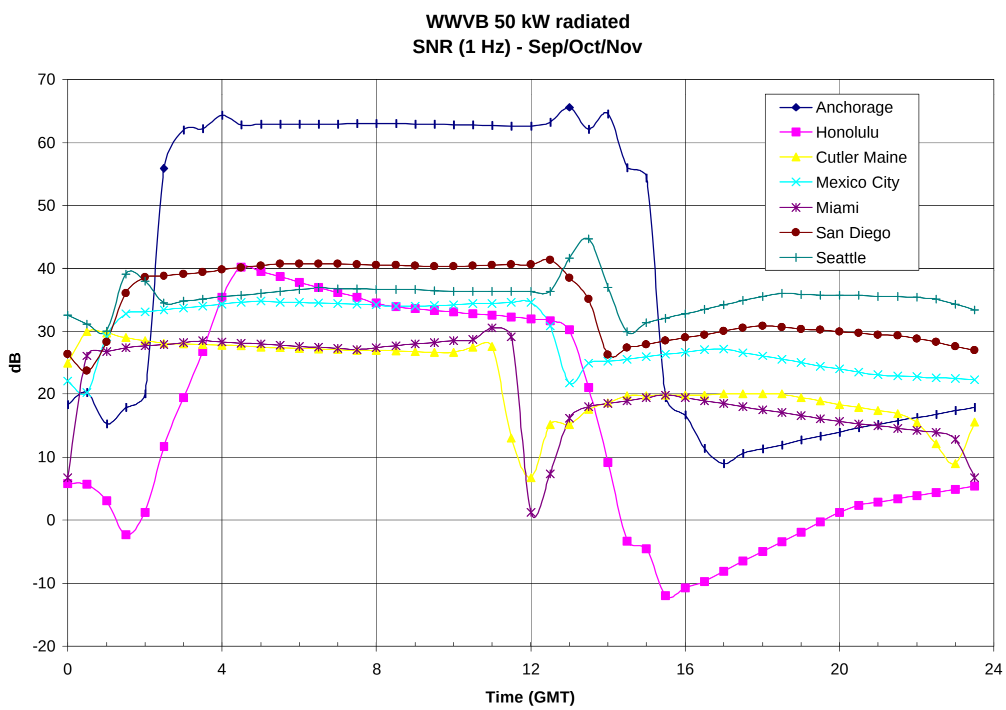

Figure 10 - Signal to noise ratio with 1 Hz Bandwidth during the autumn months.

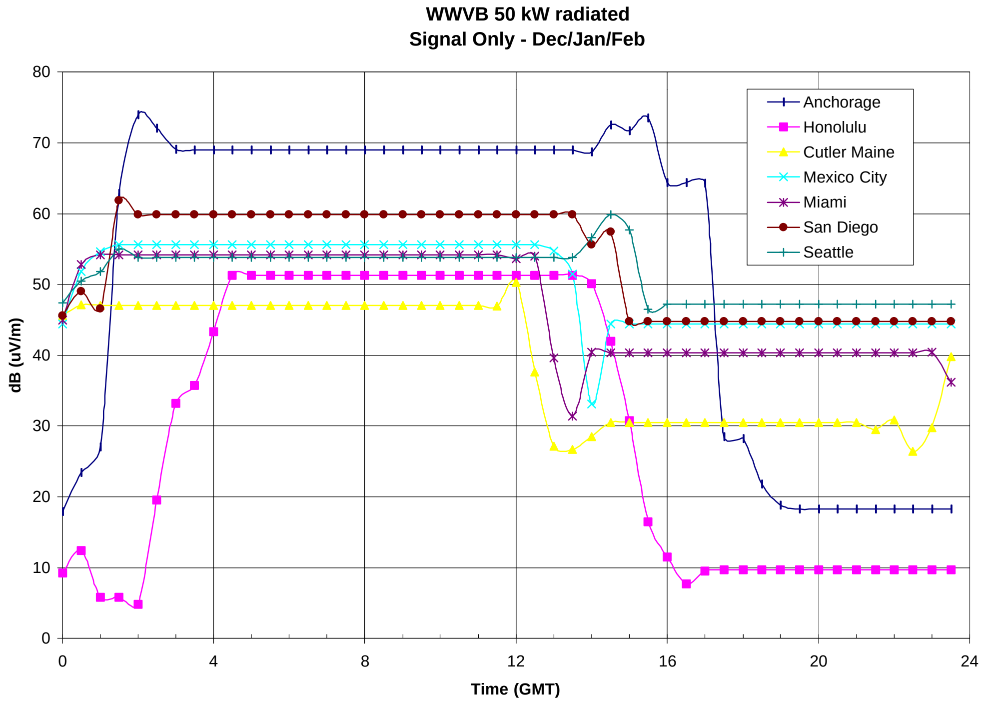

Figure 11 - Signal strength during the winter months.

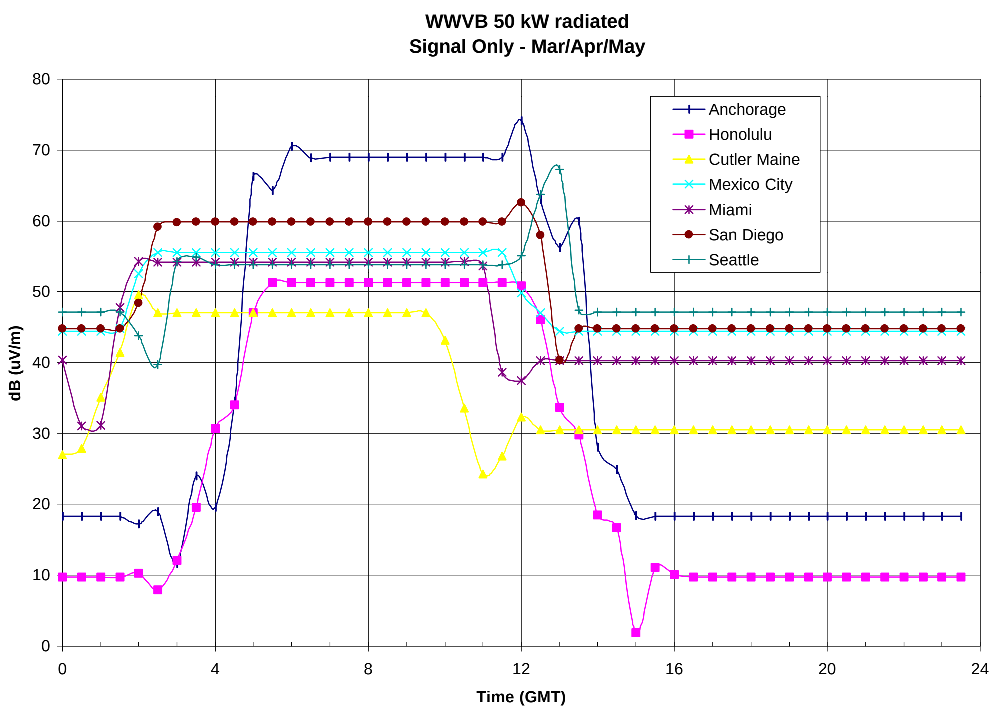

Figure 12 – Signal strength during the spring months.

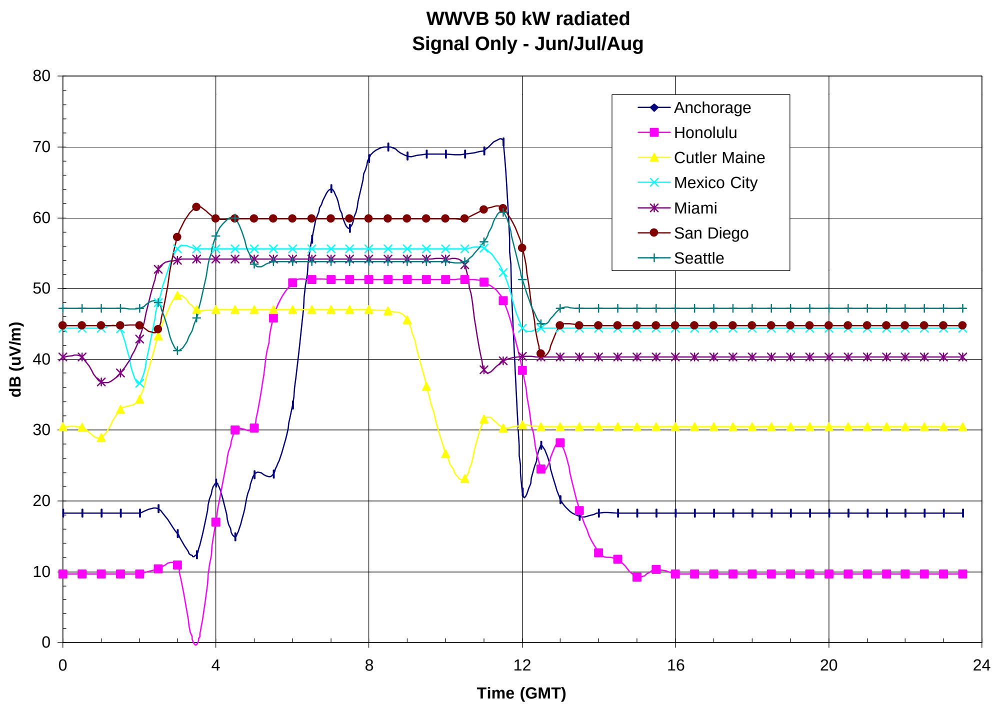

Figure 13 - Signal strength during the summer months.

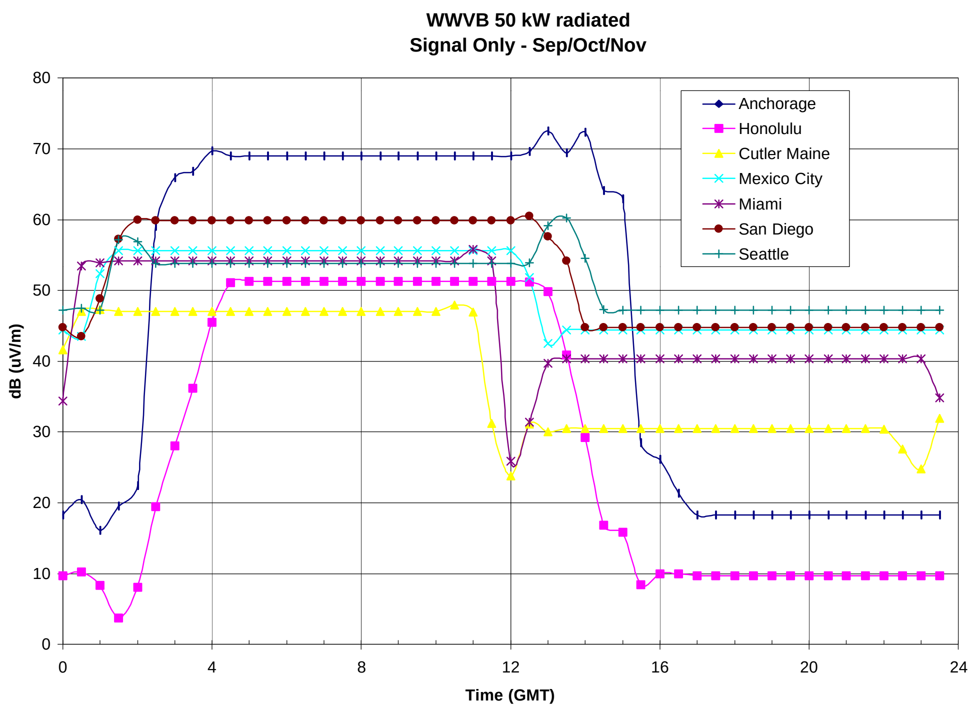

Figure 14 - Signal strength during the autumn months.