Field Trial Results of AM Transmitter Carrier Synchronization

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Abstract - *AM transmitter carrier synchronization using off-the-shelf GPS timing-reference hardware has the potential to increase the effective coverage of co-channel AM stations with overlapping contours by eliminating beat frequencies and the associated noise artifacts that serve to make the reception in the fringe areas unlistenable, both in daytime and nighttime scenarios. This paper, a follow-on to an earlier NAB publication, will address the basic carrier synchronization system design and will present results, including ongoing field measurements, that will serve to demonstrate the improvements in reception quality in the region of overlapping fringe-area co-channel contours that can be realized with low-cost transmitter carrier synchronization. In addition, this paper will discuss the successful implementation of two synchronous AM station networks utilizing multiple co-channel boosters that are currently operated by the WAPA Radio Network, covering large portions of the island of Puerto Rico.*

Background

The idea of synchronizing AM stations to improve coverage actually dates back to the mid-1920s [1]. Current quartz-controlled AM exciters on a given channel do not all function exactly on frequency, i.e., the actual operating frequency of AM transmitters will typically vary within a range of ± 3-6 Hz from nominal. The consequence of these minor differences in operating frequency is that the broadcasts in the overlapping areas of ground-wave (as well as sky-wave) coverage will produce beat frequencies that will sound like a "swishing noise", rendering both stations much less listenable. The plot in Figure 1 below [2] reveals the relative audibility of these fringe-area beats in both synchronized and unsynchronized settings; the overall result is that synchronization reduces the beat perception by some 6-10 dB, depending on the program material of both sources. Obviously, in this scenario the effective co-channel interference-limited coverage area is increased, both day and night, for all stations involved. Aside from the carrier difference-frequency beats (assumed now to be zero), there are also Doppler beats induced by the relative velocity of the vehicle receiver with respect to the various stations. In the

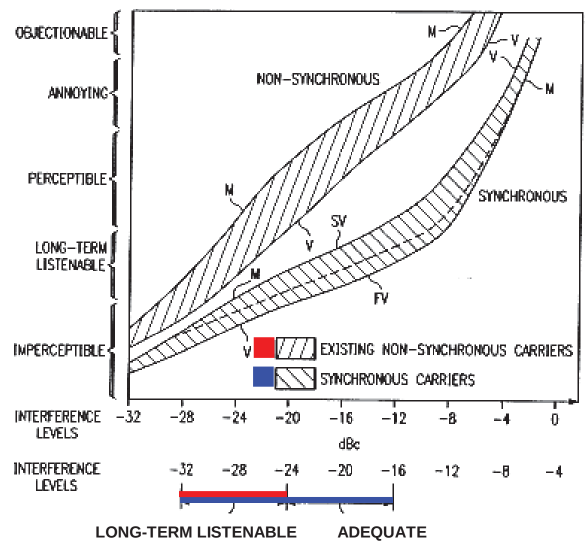

FIGURE 1 – AUDIBILITY OF CO-CHANNEL FRINGE BEATS

diagram, "M" indicates music; "V" is varied voice; "FV" is fast-tempo voice; and "SV" is slow voice. On the abscissa are the two relative interference levels; the ordinate conveys the ITU audio quality designations. The reception scenario for overlapping co-channel ground-wave signals is depicted in Figure 2 below; the equations **(1)** and **(2)** for the received signals are thus:

$$f_{beat(total)} = \Sigma_n f_{beat(n)} \quad \textbf{(1)}$$

$$f_{beat(n)} = (\mathbf{v}_{Rn} \cos \theta_n)\,(f_0/c) \quad \textbf{(2)}$$

where $f_{beat(n)}$ is the nth beat frequency in Hz, $\mathbf{v}_{Rn}$ is the receiver velocity in m/s relative to station n, θ_n is the angle of the trajectory from the radial from station n, f_0 is the original carrier frequency in Hz, n is the number of received co-channel stations, and c is the speed of light in m/s. Thus the combined Doppler-beat signal is merely the sum of the Doppler frequency components due to the relative radial velocities with respect to each station, times the inverse of the nominal RF wavelength [2].

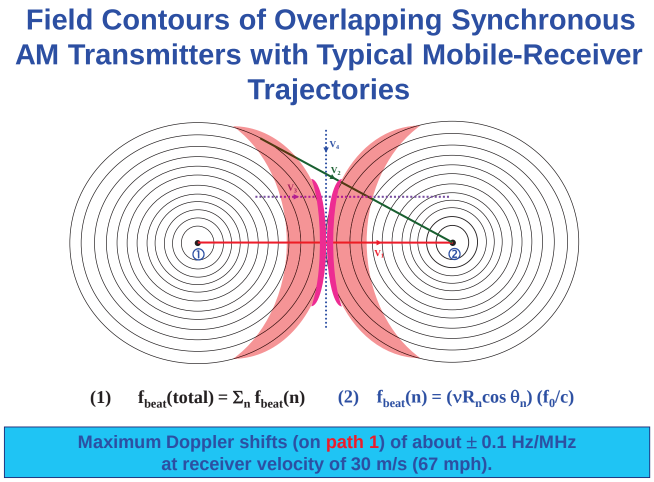

FIGURE 2 – AN ILLUSTRATION OF THE AM CO-CHANNEL GROUND WAVE CONTOUR OVERLAP AREA WHERE THE CARRIER BEATS OCCUR.

In static conditions, where cancellations due to carrier out-phasing are deeper, the regions of higher distortion are shown in light pink (purple if audio-synchronized). As will be shortly explained, however, these effects are generally no worse than in FM multipath and are well tolerated by most listeners. For moving receivers, the consequence of the Doppler effect is the *very* low-frequency beat-modulation of the audio envelope in mobile receivers, though several factors ameliorate the situation in real vehicular listening environments. First, the apparent modulation from near 0 to 0.3 Hz (typically less than 0.2 Hz) is largely suppressed by the action of the radio's internal feedback AGC circuitry, which rapidly and effectively levels these slow amplitude variations to maintain a fairly constant detected carrier magnitude. Second, the presence of relatively high levels of ambient "road noise" in the vehicle at higher speeds, particularly in the low-frequency region of the audible spectrum, serves to mask these cyclic but low-level variations. Third, local RF field irregularities, including receiver antenna pattern non-uniformities, also cause overall level variations which "dither" (randomly modulate) these cyclic field variations; these variations also tend to mask the beats. When the vehicle slows and thus produces less road noise to mask the beats, their frequencies drop to negligible values and generally fall below audibility. Finally, the dynamic nature of most types of music and voice broadcast programming also inherently tends to aurally mask these very low-frequency components. Obviously, the magnitudes of the beats will be dependent on the relative amplitudes of the two co-channel signals being received; for most areas, where the signals are at least 10 dB different in level, the resultant beats are very weak. ***Thus, the bottom line is that these Doppler effects are overall very minor.***

Compared with the standard static-receiver synchronous AM reception case, the presence of these sub-Hertz Doppler beats in *mobile* listening environments typically causes a degradation (i.e., increase) in the overall beat audibility of only about 1-2 dB compared with the curves in Figure 1. *It is important to understand that virtually all of the major benefits of synchronous co-channel station operation are still retained even for the mobile listener.*

How Does AM Synchronization Work?

It is useful to examine how the phases/delays of the audio and RF components of the AM radio signals can affect reception quality in the field, particularly in signal-overlap regions. For instance, the RF signal delay is very roughly 1 millisecond for 186 miles (corresponding to the speed of light in air). At a point equidistant from two omnidirectional, co-phased (synchronous) transmitters with equal power and propagating via groundwave mode over land paths of identical RF conductivity, the two RF signals will arrive with equal amplitudes and delays (phases). Now if we assume that the RF carriers and the sideband audio signals are precisely in phase (matched in time) as they leave the two antennas, at the exact midpoint between the two transmitters the RF signals and the detected audio will also be in phase; the signals can be added algebraically to calculate the resultant. Now for points *not* equidistant from the two transmitters, the RF signals will add vectorially as illustrated in Figure 3 below.

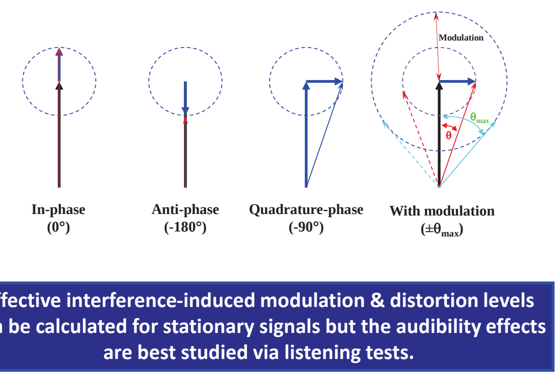

FIGURE 3 – ILLUSTRATION OF VECTORIAL ADDITION OF OVERLAPPING RF SIGNALS

In general, there will be augmentations and cancellations of the two waves occurring at spatial intervals of one-half wavelength, essentially the same as is the case for standing waves on a mismatched transmission line. Modulation distortion will be minimal near the 0°-additive points and rise somewhat at quadrature-phase contours, and peak as the summed signal approaches null at the 180° points. Obviously, near the equal-signal points, the standing wave patterns will exhibit maximum variations; in fact, §73.182(t) of the FCC's Rules defines the region of "satisfactory service" for synchronous stations as areas where the ratio of field strengths is ≥ 6 dB (≥ 2:1). ***However, the Rules as quoted did not assume the accurate time-synchronization of both audio components***; as cited by Reply Comments of Blanco-Pi and duTreil, Lundin & Rackley in the recent FCC AM Revitalization action [3], the audio time-matching significantly mitigates the apparent distortion and reduces the area of discernible distortion. The current FCC §73.182(q) Co-Channel interference limits are shown in Figure 4 below.

Class	Channel	Contour (Day) µV/m	Contour (Night) µV/m	Interfer. (Day) µV/m	Interfer. (Night) µV/m
A	Clear	100	500 (50%SW)	5	25
B	Clear Regional	500	2000 (GW)	25	25
C	Local	500	—	25	—
D	Clear Regional	500	—	25	—

Class A stations are protected to 0.1 mV/m (0.5 at night); interferers are ≥ 26 dB down.
Class B, C, D stations are protected to 0.5 mV/m (2.0 for B night); interferers ≥ 26 dB down.

FIGURE 4. CURRENT FCC §73.182(q) CO-CHANNEL RULES

The interference patterning in the synchronous overlap zone can be further reduced by phase-dithering of the booster signal(s), either in a cyclic or random-phase fashion. Terrain variations, vehicle antenna reception pattern asymmetries, buildings, and other groundwave scatterers or diffractors (i.e., multipath sources) will also reduce the magnitude of these overlap-zone disturbances via the inherent dithering of carrier phase. In moving vehicles, the audible effects will be even less, especially on speech programming. It has also been long known [4] that the distortion zones can be designed to fall over less-populated areas and major arteries. Numerous further theoretical details in the implementation of optimal synchronization of AM stations, beyond the scope of this paper, are available in [2], [5], and [6].

AM Synchronous Station Field Test Equipment Setup

We will now present audio test results in conjunction with field tests conducted involving two 1-kW Class-C AM stations on 1400 kHz — WKPT in Kingsport, TN and WGAP in Maryville, TN, which will serve to demonstrate the audio artifacts that result from the frequency difference in the overlapping regions of multiple co-channel stations. These audio files will be compared for the same geographic location with those resulting from the Global Positioning System (GPS) time-based, phase-locked carriers of the two stations' transmitters to illustrate the advantages of phase-locking of the carrier frequencies to eliminate carrier beats in the overlapping region of the two co-channel stations.

In order to conduct the field tests involving the WKPT and WGAP transmitters, we purchased Trimble S4475-15 GPS receivers and installed them as high-precision time bases for synching the carriers at the two test stations. WKPT utilizes a BE Model AM-1A transmitter and WGAP has as its main a Nautel AMPFET ND1 transmitter. The GPS antenna associated with each Trimble unit was placed on the roof of the respective transmitter buildings to facilitate robust reception of the satellite signals. At both stations the output 10-MHz square wave of the Trimble receivers was fed into the reference input of a Hewlett-Packard 3325A synthesized Function Generator, the output of which serves as a carrier reference for each transmitter, as shown in the block diagram in Figure 5 below. At WKPT the 4.5-V peak-to-peak output of the HP synthesizer/function generator was fed into the External Carrier input of the BE AM-1A after moving the jumper on the exciter board from the internal crystal position to the external input position. The synthesizer/function generator was set to 1400 kHz. At WGAP the 6-V P-P output of the synthesizer/function generator was coupled into the Nautel AMPFET transmitter exciter via its External RF input.

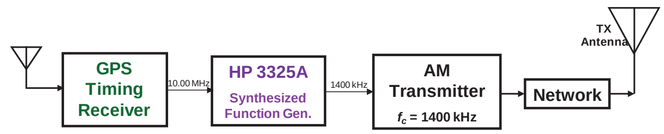

FIGURE 5. BLOCK DIAGRAM OF THE INSTRUMENT SETUP AT EACH SYNCHRONIZED OPERATION AM STATION.

A photo of the synchronization test equipment setup at WKPT is shown in Figure 6 below.

FIGURE 6. PHOTO OF THE EQUIPMENT SETUP AT WKPT

A photo of the sync test equipment setup at WGAP is shown in Figure 7 below.

FIGURE 7. PHOTO OF THE EQUIPMENT SETUP AT WGAP

AM Synchronous Station Test Plan

We identified a series of monitoring locations approximately midway between the two stations where the carrier beats produced by the two overlapping ground wave contours could be clearly heard. A Google map showing the location of the two stations and the monitoring locations is provided in Figure 8 below.

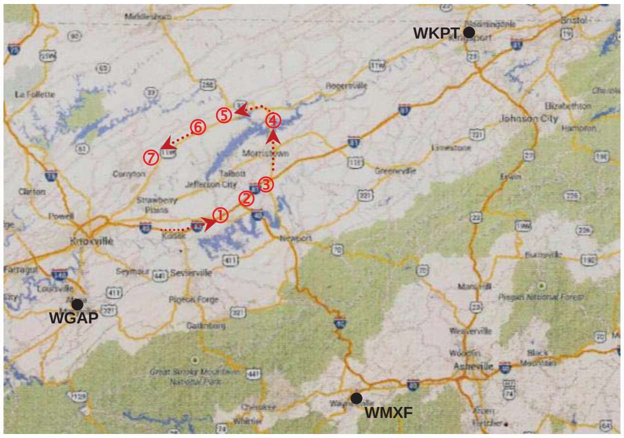

FIGURE 8. MAP SHOWING THE LOCATIONS OF THE TWO TEST AM STATIONS AND THE MONITORING LOCATIONS

While maintaining the WKPT transmitter on precisely 1400 kHz, we dithered the frequency of WGAP by either 1 or 2 Hz and then restored it to 1400 kHz for periods of 1 minute each and monitored the reception for the two conditions of offset and synchronized carriers. In the monitoring vehicle (a 2005 Toyota Camry) we utilized a sinusoidal DC-to-AC inverter plus a Corcom 3ET1 high-performance AC line noise filter to power a laptop computer and a Carver Model TX-11a wideband AM tuner. The output of one of the speakers in the monitoring vehicle was wired to a handheld Tascam DR-05 to facilitate 16-bit digital recording of the AM car receiver audio. The line output of the Carver tuner was also recorded to enable comparison of reception on this high-quality AM receiver with that of the sensitive but narrowband car radio.

AM SYNCHRONIZATION FIELD TEST RESULTS

The test path, as depicted on the map, proceeded eastward from Knoxville on I-40, turned northeast onto I-81, turned northwest onto US-25E, and returned to Knoxville via US-11W through Rutledge. Stops to record stationary data were made at the indicated points, though the audio data was recorded continuously throughout the trip, for roughly 100 minutes' duration. Overall, the results were largely as expected from the earlier lab tests [5], though with a small amount of beat interference from WMXF in Waynesville, NC, which was not synchronized for this test but whose signal was greatly attenuated by the intervening mountains. The WKPT-WGAP beats at 1 or 2 Hz were clearly audible during the offset intervals but were notably absent under synchronized conditions. Without the carrier beats, only undistorted background audio from the weaker co-channel station remained; as expected, the overall fringe-area listenability was significantly improved.

CURRENT AM SYNCHRONOUS BOOSTERS

The concept of utilizing AM co-channel GPS-based synchronous boosters to augment the coverage of existing AM stations is not new in the US broadcast market. There are currently eight AM stations in the United States and Puerto Rico as listed in Table 1 that are utilizing AM synchronous boosters (denoted*). The WAPA Radio Network in San Juan, PR (WAPA and WISO) has been successfully operating AM synchronous boosters without listener complaints for more than 20 years. All of these boosters are currently being operated under FCC experimental licenses. Very importantly, in contrast to many earlier synchronous AM implementations, both these networks have employed precise delay-matching of the RF signals ***and*** the respective audio modulation signals from each transmitter; this greatly reduces the magnitude and extent of the signal-distortion "mush" zones, to a level comparable to those experienced with FM stations in hilly terrain. Based on current GPS receiver technology and the accumulated experience of these AM stations currently operating AM synchronous boosters, it is our opinion that this technology should be immediately licensed by the FCC as a flexible, low-cost means to extend the coverage of existing non-directional or directional stations, especially in populated but poorly covered areas.

TABLE I
CURRENT U.S. AM SYNCHRONOUS AM & BOOSTER STATIONS

STATION	FREQ. (kHz)	POWER	LOCATION
WRJR	670	20 kW/3 W(N)	Claremont, VA
WR2XJR*	670	700 W(N)	Portsmouth, VA
WAPA	680	10 kW(U)	San Juan, PR
WA2XPA*	680	400 W(D), 570 W(N)	Arecibo, PR
WIAC	740	10 kW(U)	San Juan, PR
WI2AXC*	740	500 W(D), 100 W(N)	Ponce, PR
KKOB	770	50 kW(D/N)	Albuquerque, NM
KKOB*	770	230 W(U)	Santa Fe, NM
KCOH	1230	1 kW(U)	Houston, TX
KCOH*	1230	410 W(U)	Houston, TX
WISO	1260	2.5 kW(U)	Ponce, PR
WI2XSO*	1260	5 kW(D), 1.8 kW(N)	Mayaguez, PR
WI3XSO*	1260	5 kW(D), 4.8 kW(N)	Aguadilla, PR
KDTD	1340	1 kW(U)	Kansas City, KS
KDTD*	1340	200 W(U)	Kansas City, KS
WLLH	1400	1 kW(U)	Lowell, MA
WLLH*	1400	1 kW(U)	Lawrence, MA

Consider the example of the synchronous boosters being operated by the WAPA Radio Network in Puerto Rico, a small but highly populated island (3.7 million people in a 100-mile by 35-mile area). The unpopulated areas are scarce and small. Regarding the three synchronized WISO transmitters operating on 1260 kHz, a typical listener can drive his vehicle from the northwest down to the west, southwest, and south areas of the island without detecting a problem in the station's signal quality due to the overlap of the synchronized signals; the two 5-kW boosters and the 2.5-kW main station have overlapping coverage areas as shown in the coverage plot of Figure 9 below.

The green area is the 2 mV/m overlap of the WI2XSO and WI3XSO boosters. It is important to note the substantial 2-mV/m and 5-mV/m overlap area between the two boosters. WI3XSO could be considered as a "fill-in" synchronous booster for WI2XSO, since the WI3XSO transmitter site is *inside* the 2mV/m coverage contour of WI2XSO. The orange area denotes the 2 mV/m overlap of WI2XSO and WISO. It could be said that WI2XSO is a contour-expanding booster for WISO, since the WI2XSO transmitter site is well *outside* the 2 mV/m contour of WISO. Similarly, Figure 10 shows the WAPA system contours.

The use of synchronous AM boosters to explicitly increase the coverage area of existing stations in populated areas should not be impaired or restricted, so long as no significant increase in interference to either co-channel or adjacent-channel stations would be so generated, in full compliance with existing FCC allocation Rules. In addition, boosters may be non-directional or directional, as exemplified by the existing installations listed above in Table I.

The extended experience of the WAPA networks in Puerto Rico has confirmed the efficacy of these techniques.

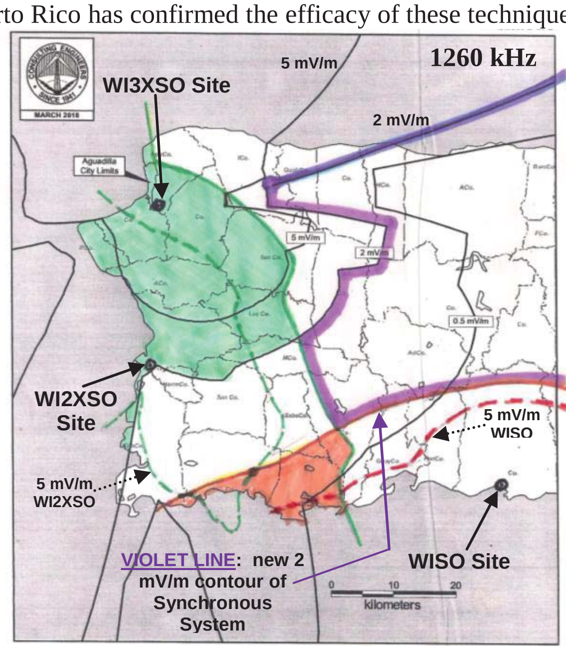

FIGURE 9 — PREDICTED COVERAGE CONTOURS OF WISO AND ITS WI2XSO AND WI3XSO SYNCHRONIZED BOOSTERS

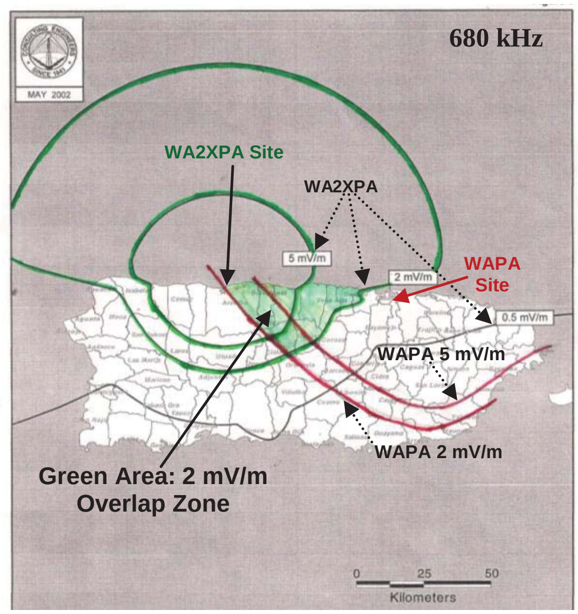

FIGURE 10 — PREDICTED COVERAGE CONTOURS OF WAPA AND ITS WA2XPA SYNCHRONIZED BOOSTER

Based on reports from a local (PR) radio engineer, who is a more qualified listener, some *slight* cancellations are evident in the overlap-area audio, though probably less severe than those produced by a typical directional antenna pattern null while driving; in fact, no complaints about perceived signal distortion from the general listening public are ever received. Several other observations: first, when driving over a highway the cancellations are practically unnoticeable; second, while driving if one makes a stop at the specific site the cancellation occurs (or if a home receiver is located at the specific place a cancellation occurs), the spatial cancellation would be noted as a slight-to-moderate distortion in the audio, but not enough to impede listening to the station. Moving a few feet eliminates or practically eliminates the most critical cancellation distortion. In the case of home receivers, the listener won't likely notice the cancellation because of the radio's directional ferrite antenna; in vehicles, the non-uniformity of the antenna pickup pattern will also serve to mask the cancellations. Two of the authors, Eng. Blanco-Pi and his son Jorge, in the implementation of their AM synchronous booster systems, note that there are several practical points that should be observed when optimally synchronizing AM stations: **(1)** If you utilize a transmitter without an output network at one synchronous site and a transmitter with an output network at the other site, you will have problem in accurately synchronizing the signals. ***Both transmitters have to operate either with or without an output network (this equalizes the RF delay).*** **(2)** If you use audio processors at both transmitters, both should be the same type and set up identically in their operational parameters. **(3)** Don't use an audio path between synchronized stations where you don't have control over the equipment, the path being used, or (stated more simply) over the delay in the paths. If you use, for example, a fiber-optic cable from an external provider as opposed to a microwave link, you will never be able to properly synchronize the audio. (**4)** Remember, the net audio delay path difference to be compensated will be on the order of microseconds, not milliseconds. **(5)** If you have main and alternate/auxiliary transmitters that are not of the same type, you will likely have to use another delay unit to compensate between the difference in the transmitters' delays. For example, if you use a Harris DAX-5 transmitter as the main and a GATES-5 unit as a backup, you will have to insert a 0.11-μs delay at the GATES-5 audio input to compensate for the higher throughput delay in the DAX-5.

It is thus straightforward to synchronize the RF frequency, the audio phase, and/or delay of the synchronized stations once you know how to do it. The system, once set up, is very stable and generally won't need to be readjusted unless there is an equipment change or failure. Figures 11 and 12 below provide details of typical site audio and RF/timing synchronizer units deployed by the WAPA Network in PR.

FIGURE 11 – WISO AUDIO SYNCHRONIZER UNIT

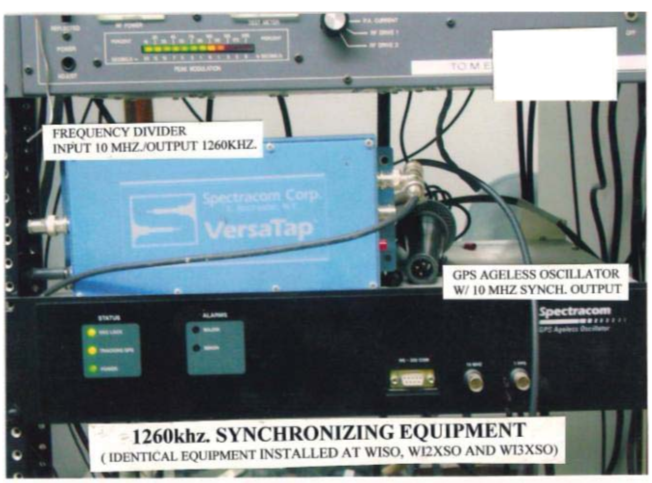

FIGURE 12 – WISO RF SYNCHRONIZATION EQUIPMENT

As is clearly evident from the photos in Figures 13-14 below, the boosters are in every respect technically identical to a standard AM transmitting installation, except for the addition of the RF and audio synchronization gear. Several of the WAPA boosters have directional antenna arrays and are able to provide strong-signal coverage to population areas not adequately served by the main stations. Other practical uses of low-power, low-cost synchronous AM boosters would include useful fill-ins for covering populated areas lying in pattern nulls. Boosters can further be used daytime and/or nighttime as needed to provide improved coverage of outlying suburbs (especially true for Class-C stations). Obviously, the utilization of additional boosters can be easily handled under existing AM allocation rules.

FIGURES 13 & 14 – EQUIPMENT AND EXTERNAL VIEWS OF THE WI2XSO SITE IN MAYAGUEZ, PR

CONCLUSIONS

A low-cost synchronization scheme to minimize beat-related interference among co-channel AM stations has been discussed. Although the general technique of *local* synchronization has been known and studied in the past, including for AM stations, only recently has the feasibility of assembling an *economical* wide-area (continental to worldwide) synchronization system for AM broadcasting emerged, largely due to the availability of low-cost (< $100) GPS timing receivers and inexpensive electronic devices such as microprocessors and logic chips. We anticipate that for a cost between $1-2K, a GPS-referenced frequency-synchronizer unit can be deployed at transmitter sites. The system would be capable of holding both modern and older transmitters to well within 0.5-1 ppb of the assigned frequency, thus essentially eliminating carrier beat interference among co-channel AM stations. According to our lab and field tests, the net result would be a near doubling of the existing ***co-channel interference*-limited** coverage radius of stations (and nearly a quadrupling of the serviceable reception area), as depicted below in Figure 15.

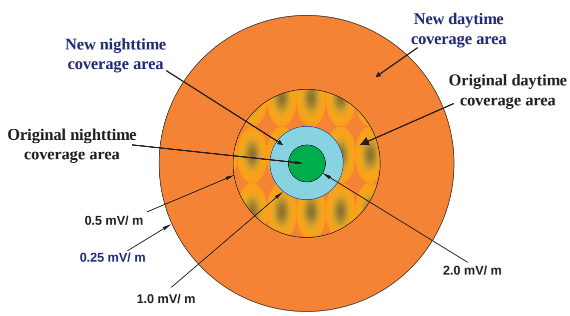

FIGURE 15 — EFFECTIVE SYNCHRONOUS DAY/NIGHT INTERFERENCE-LIMITED COVERAGE IMPROVEMENTS

For a hypothetical station in a high-conductivity area with interference-limited contours (i.e., on Class A or B channels), a 6-dB reduction in interference due to beats can provide a corresponding almost 2:1 gain in listenable range (the gold and blue dotted annular regions). Obviously, other factors such as power-line noise may well intervene, ***but both daytime and nighttime listenable areas will improve significantly.*** Although essentially all stations will benefit during early-morning and near-sunset (critical) hours, this is of paramount importance to local Class-C stations, which often can no longer cover their population centers at night due to suburban sprawl, as well as Class-D stations with very limited nighttime power levels.

The broad use of wide-area AM synchronization technology will also significantly improve long-distance sky-wave reception by minimizing the carrier beat effects from co-channel interfering signals, and the same synchronization techniques have been successfully proven for over 20 years in overlapping full-power booster implementations in Puerto Rico. Practical low-power boosters to fill in directional nulls (equivalent to FM translators) are also now feasible. Figure 16 below provides a typical implementation scenario.

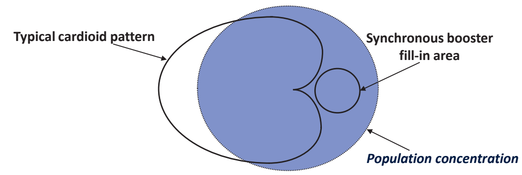

FIGURE 16 – SYNCHRONOUS AM BOOSTER FOR FILL-IN

The major deployment issue for synchronous AM systems is not really technical or even economic, but political — to make wide-area synchronization work optimally, all broadcasters must join in. For the majority of stations to rapidly benefit, we believe the FCC must mandate the technology. From our perspective, the low cost ($1-2K) should not constitute an economic hardship for any station, particularly when weighed against the major coverage gains to be realized. Certainly, stations near the Canadian and Mexican borders will need the additional cooperation of our neighboring nations' broadcasters, but the same benefits will apply to them as well. Further, the use of AM synchronous boosters can provide a huge benefit to virtually ***all*** AM stations in better covering key audience areas. Of course, the major issue of RFI from power lines, cable/DSL services, LED traffic signals, and consumer devices in the home still remains; broadcasters must assertively address these problems with the FCC and local utilities to preserve the integrity and availability of AM radio for future generations.

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