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NATIONAL RADIO SYSTEMS COMMITTEE

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AM Carrier Synchronization Guideline
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FOREWORD

Co-channel interference for AM stations can be exacerbated by even small differences in the carrier frequencies of the stations. While “co-channel” implies that the stations are on the same nominal frequency, a small difference in the carriers’ specific instantaneous value causes additional low-frequency artifacts in the receiver as the two carriers mathematically combine to create a difference or “beat” frequency. Additional stations’ signals on the channel (at least, those above the noise floor) make the situation correspondingly worse.

However, accurate carrier frequency synchronization of the various geographically distributed AM transmitters on the channel can in practice greatly reduce or eliminate such artifacts. Such interference reduction has the potential to increase the effective coverage of co-channel AM stations with overlapping contours by eliminating these beat frequencies and the associated noise artifacts that serve to make the reception in the fringe areas unlistenable in daytime, critical-hours, and nighttime co-channel scenarios. This is especially beneficial where the desired-to-undesired (D/U) signal ratios are noticeably less than the nominal FCC-designated 26 dB co-channel protection figure. Further, precise frequency/phase synchronization can facilitate the use of additional close-in low-power AM booster transmitters to provide additional coverage of population centers, particularly those located in relative nulls of directional patterns or otherwise weak-signal or high-noise areas. The benefits of wide-scale synchronization accrue to both analog and digital AM stations via the elimination of co-channel carrier beats and the consequent reductions in receiver disturbances due to those beats and the resulting sideband intermodulation components.

This document provides a comprehensive summary of synchronous AM operation and discusses the methods and types of hardware available to achieve high accuracy, easily implemented AM carrier synchronization using both current and legacy transmitters. Synchronization is inexpensive and straightforward to implement using low-cost, off-the-shelf GPS timing-reference hardware. Key system performance specifications to achieve effective carrier synchronization in standard-spacing co-channel scenarios are discussed herein. This Guideline document focuses on standard AM carrier-frequency synchronization techniques, where specific carrier-phase control is not necessary. Another topic for future work is information needed to successfully implement close-in repeaters (local AM boosters) to augment reception in weak-signal or high-noise areas closer to the transmitter, such as in directional antenna nulls. It is apparent that given the very minimal cost, synchronization can make an improvement that might otherwise be several orders of magnitude more expensive (e.g., increasing transmit power) in order to achieve a comparable effect.

The information contained in this NRSC Guideline was compiled and reviewed by the AM Improvement Working Group (AIWG), chaired by Brian Henry, Henry Communications, a sub-group of the AFAB Subcommittee of the NRSC, chaired by Martin Stabbert, Townsquare Media.

The NRSC is jointly sponsored by the Consumer Technology Association and the National Association of Broadcasters. It serves as an industry-wide standards-setting body for technical aspects of terrestrial over-the-air radio broadcasting systems in the United States.

AM CARRIER SYNCHRONIZATION GUIDELINE

1 SCOPE

This is an informative guideline document which provides information on synchronization of AM carriers by AM broadcasters as a means to reduce the mutual interference between AM stations. The G102 Guideline provides AM carrier synchronization application information for interested equipment manufacturers, engineers, and broadcasters.

Pertinent system specifications, including frequency/phase stability and AM transmitter interfacing requirements, are discussed herein. Two principal application spaces are delineated: (1) standard-accuracy conventional co-channel scenarios, including daytime groundwave and nighttime skywave interfering signals; and (2) high-stability AM synchronous-repeater arrays for covering larger local areas. Both types of systems have been previously deployed under FCC experimental authorization and have successfully demonstrated over many years improved local coverage without significant interference to distant stations. This Guideline will focus on the former category; specific information relevant to the latter issue of AM synchronous boosters is left for future work.

2 REFERENCES

2.1 Normative References

This is an informative specification. There are no normative references.

2.2 Informative References

The following references contain information that may be useful to those implementing this guideline document. At the time of publication, the edition(s) or version(s) indicated were valid. All references are subject to revision, and parties to agreements based on these references are encouraged to investigate the possibility of applying the most recent editions of the references listed below.

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2.3 Symbols and Abbreviations

AFAB	AM & FM Analog Broadcasting Subcommittee
AGC	Automatic Gain Control
AIWG	AM Improvement Working Group
AM	Amplitude modulation
CDMA	Code-Division Multiple Access
CEA	Consumer Electronics Association
CQUAM	Compatible Quadrature Amplitude Modulation
dBc	Decibels relative to carrier level
DDS	Direct Digital Synthesizer
DSB	Double-sideband
D/U	Desired-to-Undesired signal ratio
EMI	Electromagnetic Interference
FCC	Federal Communications Commission (U.S.)
FPGA	Field-Programmable Gate Array
GPS	Global Positioning System
GPSDO	GPS-disciplined oscillator
IBOC	In-Band/On-Channel
IEEE	Institute of Electrical and Electronic Engineers
IQM	Incidental Quadrature Modulation
ISO	International Standards Organization
NAB	National Association of Broadcasters
NRSC	National Radio Systems Committee
N/A	Not Applicable
NCO	Numerically-Controlled Oscillator

OCXO	Oven-Controlled Crystal Oscillator
ORNL	Oak Ridge National Laboratory
PLL	Phase-Locked Loop
P-P	Peak-to-peak
QPM	Quadrature Phase Modulation
RF	Radio Frequency
RFI	Radio Frequency Interference
RMS	Root-Mean Square
RSS	Root-Sum-Square
SFN	Single-Frequency Network
SIR	Signal-to-Interference Ratio
TBD	To be Determined
TCXO	Temperature-Compensated Crystal Oscillator

2.4 Definitions

In this Guideline the following definitions are used:

Synchronization	The full time/phase and frequency alignment of two or more signals, typically achieved by locking the controlled signals to a common reference, within a given accuracy or permissible error. Succinctly termed “phase-frequency lock”.
Syntonization	The accurate frequency alignment of two or more signals, typically achieved as above by locking the controlled signals to a common reference, within a given accuracy or permissible error. The relative phase of the signals is not specified, though a maximum rate of differential phase change versus time is generally implied. Often loosely called “synchronization” in standard parlance, i.e., “frequency-locked” but not “phase-locked”.
HD Radio™	Trademark (of Xperi, Inc,) for the digital AM and digital FM transmission technology authorized by the FCC. Note that the use of the term in NRSC documents shall be interpreted as the generic term “IBOC” and shall not be construed as a requirement to adhere to undisclosed private specifications that are required to license the HD Radio name from its owner.

3 BACKGROUND

3.1 Precision Carrier Lock / Synchronization Benefits for AM Broadcasters

Regardless of the class of AM broadcast facility (A, B, C, or D), there will be benefits to almost every station that undertakes carrier frequency synchronization. The benefits from synchronization will vary from station to station due to the complex nature of the AM broadcast band, which encompasses a 3:1 frequency span and exhibits varied propagation and noise characteristics from 530 kHz to 1710 kHz.

Fundamentally, the use of carrier frequency synchronization reduces the beat note, and resultant intermodulation (IM) on an envelope detector or potential IM on synchronous detectors, the latter being dependent upon the phase locked-loop corner frequency of the synchronous detector system. Furthermore, there are some DSP envelope detector implementations which inadvertently create noise-like byproducts that manifest themselves as hard clipping transients on weak signals. These effects are aggravated by carrier beats. Carrier synchronization can improve reception on these receivers.

Specific to the various classes of AM stations, the following improvements in listener experience may also be observed:

- For Class A stations and many other stations operating at power levels of 10 kW and higher that also utilize the dominant variant of Modulation-dependent Carrier Level (MDCL) technology, Amplitude Modulation Companding (AMC), the use of higher average modulation levels can cover much of the loss of signal to noise ratio to the listener due to a 3-6 dB reduction in carrier power level when modulation is present. It will not, however, improve the effects of beat-note IM created by the differential frequency between two or more carriers. The increased modulation density and increased power contained within the additive sidebands will not cover up the increased effect of a beat-note when the carrier level of the desired station is reduced in power level by the use of MDCL.

  For example, if 6 dB of AMC is utilized on a 50 kW station, the resultant carrier power level during periods when the carrier is fully modulated is reduced to 12.5 kW. The received field strength as measured would drop to one-half the unmodulated carrier level. A 2 mV/m field strength becomes 1 mV/m with modulation. Unfortunately, a co-channel interferer does not undergo the same drop in field strength unless it, too, is utilizing AMC. The level of the beat-note is, therefore, up to double that if AMC is not in operation at the interfering station. Synchronizing the carriers of both stations essentially eliminates the beat-note; thus effectively eliminating the side-effects of the beat-note and further improving the cost-saving benefits of MDCL. Modulation density cannot cover the effects of beat note(s); it is solely dependent upon the ratio of instantaneous carrier field strengths at any chosen location.

  Further, listeners of Class A stations utilizing skywave signals will also benefit from carrier synchronization for the same reasons other classes of stations will obtain benefit as a result of the reduced beat-note IM.

- Class B, formerly Regional stations, operating on Regional channel allocations, will likely experience improvements in coverage both day and night. Some Class B stations utilize MDCL; the benefits are identical to those of the Class A stations and can occur day and night. Furthermore, Class B stations operating with Critical Hours power allotments and conditions do so due to the likelihood of co-channel interference. nighttime reception improvements will result when one, or a small number of co-channel interference contributors exist.

- For Class C, formerly “Local / Class IV” stations, the nighttime benefits of synchronous carrier lock are not as apparent. Since the typical Class C station endures co-channel interference from many carriers during nighttime operations, the combined beat-note produced approaches that of a pseudo-random frequency offset effect. Furthermore, additive modulation components from the multiple co-channel interferers also significantly limit the coverage area of the station at night.

Despite this effect, Class C stations will benefit from synchronous carrier lock during the daytime and during critical hours where co-channel interference at a given physical location is primarily contributed by one, or a few, co-channel stations. Daytime and critical hours operations of Class C stations will experience an effective extension in coverage area due to the suppression of the beat-note and its resulting IM products. The effects are much like those of other Class B and Class D stations typically protected to the 0.5 mV/m contour by a 26 dB D/U ratio. Rural and smaller town stations that often have listeners beyond their protected contours will likely find that, once their facility as well as the co-channel facility creating the beat-note are synchronously locked, both stations may become listenable to their 0.25 mV/m and even 0.1 mV/m contours during the day (provided no significant man-made noise is present). This is most important to broadcast facilities serving farming communities and in sparsely populated regions of the country.

- Class D stations, formerly Daytime stations as well as other noted situations, below, also stand to experience coverage gains from carrier synchronization. Many Class D stations were fitted into the allocations table by barely meeting co-channel protection limits. As a consequence, these stations often experience beat-note issues in locations where listeners must endure the effects of co-channel interference. As in other above-listed situations, reception improvements will be made through the use of precise carrier synchronization. Many Class D stations were formerly Daytime-only operations that were subsequently granted very low nighttime powers in the mid-1990s. While these stations are offered no nighttime protection from co-channel signals, synchronization of the carriers will suppress some of the most offensive effects of co-channel interference.
- Finally, we are experiencing the “down-building” of many facilities. In these cases, directional arrays, occupying large tracts of valuable land, are being deconstructed to simpler arrays to retain daytime service or, in other cases, the station is reduced to a single, omnidirectional tower with very low nighttime power levels that are no longer offered previous nighttime protection limits. Just as in other Class D operations, these stations, also now often designated Class D, will also benefit from carrier synchronization. Since the interference thrust upon these stations is generally sourced from one or a few co-channel stations, improvements in audio quality and listenable service area increases are expected.

RF carrier synchronization is of benefit to almost every broadcast facility. It requires action on the part of all broadcast stations if the full benefit is to be expected and observed. Synchronization is not difficult today and is available through several low-cost methods including GPS-based carrier lock. With the level of external interference AM broadcasters are exposed to today, everything that can be done to reduce interference is important and beneficial. This includes action internal to our community to reduce the potential of self-generated interference within our own confines.

3.2 Improving AM Reception Quality and Increasing Listener Areas

The concept of synchronizing the carrier frequencies of co-channel AM stations to reduce mutual interference is hardly new. Since the mid-1920s, numerous studies and experiments with synchronizing AM signals have been conducted, with overall positive results, including on clear channels at distance [1], [2] and in close-in urban environments [3]. More recently, multiple papers, published by the IEEE and NAB in the 2007-2015 time frame, [4], [5], [6], [15] and four U.S. Patents originally issued to Oak Ridge National Laboratory (ORNL), [7]-[10], but now all in the public domain, described a straightforward but highly accurate carrier-frequency synchronization scheme for actively, automatically locking multiple, remotely located AM broadcast transmitters to a common frequency/timing reference source such as GPS. The extremely tight frequency lock (long-term to ~1 part in 10^9 or better) permits the effective elimination of audible and even sub-audible beats between the local (desired) station’s carrier signal and the distant stations’ carriers.

Generally, an AM radio listener during the evening and nighttime hours, and to a somewhat lesser extent in the early morning, receives undesired skywave signals from several distant co-channel stations as well as the desired local (groundwave) signal. These carrier-beat components in the current non-synchronized channel environment cause annoying modulations of the desired station's audio at the receiver and concurrent distortion of the audio modulation from the distant station(s) and thus often cause listeners to "tune out" due to the audibly poor reception quality.

The effect is a decrease in reception quality as a result of carrier beat effects which becomes noticeable when the overall desired-to-undesired (D/U) co-channel signal levels at the receiver are less than 20 dB, which is typical of many fringe-area reception scenarios, including in daytime fringe areas as well as much more widely during critical hours and at night. This is separate from background bleed-through of the co-channel interfering audio modulation, which may become audible at a greater D/U ratio than do carrier beat effects. Generally, FCC allocation rules strive for a co-channel D/U ratio of at least 26 dB, but distant listening, as well as variance in groundwave signals and fading in nighttime skywave signals may result in listening conditions below this value. The co-channel beat effects are noticeable because the average carrier power is on the order of 10 dB above that of the typical levels of the sideband modulation components, and the inter-carrier beats will dominate the receiver's AGC and thus modulate the audio level. Along with co-channel bleed-through and potential RF environmental noise, these beat-related effects are a contributing factor in the degradation of AM fringe-area reception quality at all hours and the resulting loss of outlying listeners for almost all AM stations.

Perhaps the most deleterious aspects of these beats are the high-level artifacts (volume modulation, cyclic distortion, and pronounced flanging/phasing effects) that may quickly induce listener tune-outs. This situation is not only progressively worse further into the fringe areas of the desired stations (usually in the outer suburbs of the city of license), but also occurs much closer in, during critical hours and nighttime, especially in the deep nighttime nulls of directional stations.

If, however, we employ precise carrier-frequency synchronization, all of these signals' carriers can be held to within about 0.01-0.001 Hz (1-10 mHz) of each other, and any resulting beat frequencies will be of such long periods that the beats will be effectively suppressed by the action of the receiver's AGC circuitry and become completely unnoticeable to the listener. The significant reduction or elimination of the beats and related effects achievable via synchronization will enlarge the effective co-channel interference-limited listening area of the desired station and simultaneously reduce the corresponding interference of the local transmitter to the distant stations as well.

In addition, AM stereo (C-QUAM) reception will be improved by minimizing the dynamic phase shifts induced by co-channel interfering signals; IBOC signal reception will also benefit via reduction in beats from co-channel analog signals. It is essential, however, to understand that these co-channel beat effects are totally separate from local radio noise interference [EMI] due to arcing power lines, switching power supplies, fluorescent-lamp ballasts, vehicle ignitions, traffic signals, and the like.

Use of precise carrier frequency control to synchronize with co-channel stations will not be equally effective for all AM stations. Nighttime operation on some channels may have an RSS (combined) skywave interference level from numerous stations that is larger than the worst co-channel skywave interferer. The RSS combined noise around the fringe area of a station may be great enough to overcome the benefit of frequency synchronization with even the worst co-channel skywave interferer.

This RSS level for skywave co-channel stations, and the level of the worst co-channel skywave interferers must be determined with a computerized allocation tool and database, which may involve some cost. It is not possible to generalize the conditions, as every station case is different. However, the congestion of Class C AM stations results in skywave RSS levels that are challenging to overcome. Class D stations, particularly in the eastern half of the U.S., also have a large nighttime congestion. Class B stations can vary widely in skywave RSS level, but can be expected to benefit from synchronization. Class A stations are clear channel facilities with large nighttime service areas and should largely enjoy the benefit of carrier frequency synchronization.

The geographic separation of daytime co-channel stations results in predicted D/U ratios of 26 dB or more at a station's protected service contour. This ratio is usually greater than the threshold at which co-channel beat effects become audible. However, many stations have mobile listeners at distances well outside the service contour, where a groundwave D/U ratio may be a problem with a co-channel neighbor. (Most AM stations are well aware of their own co-channel neighbors and where daytime interference is known. These are likely candidates for mutual carrier frequency synchronization.)

While allocation rules separate the daytime signals between most co-cannel stations, recent changes in FCC rules for post-sunset and pre-sunrise operating power can produce temporary skywave propagation that extends interference into part of a co-channel station's service area. Again, these are known to most station operators and this effect can be easily verified by visiting coverage limit areas at dusk that are closest to a neighboring co-channel neighbor that exercises post-sunset and pre-sunrise operation. Stations with this condition may have a particular benefit from mutual carrier frequency synchronization.

3.3 Methods used for AM carrier synchronization

The automatic GPS-locked frequency-control hardware described in this document and the references is relatively inexpensive, requires no periodic recalibration, has essentially zero long-term drift, and could alternatively employ other wide-area frequency references of suitable accuracy, including broadcasts from WWVB, LORAN-C, or equivalent sources. The basic configuration of an adequate commercially available GPS-disciplined oscillator (GPSDO) which solves this problem is extremely simple and typically costs around $200 US (including the GPS antenna).

The main oscillator Is normally a conventional high-stability temperature-compensated or ovenized quartz-crystal type. To counter long-term drifts, the oscillator is automatically adjusted to track a high-precision local source of standard frequency obtained from a specialized GPS receiver, usually at 10.000 MHz. This very stable local reference frequency is then used as a clock for a standard digitally implemented frequency synthesizer, which is programmed to generate the specific (AM broadcast) transmitter carrier frequency desired.

The stability of the disciplining source, typically ~ 1 part in 10^9 to 10^{11}, is thus transferred to the final AM transmitter carrier output frequency. Most modern, synthesizer-based transmitters can directly lock to the precision disciplined 10-MHz source, while older units usually require references at either 1×, 2×, or 4× the final frequency, which can be obtained via standard frequency-synthesizer hardware. In these latter cases, the existing transmitter oscillator can be replaced, or alternatively the crystal can usually be satisfactorily "pulled" via injection locking.

Note that some forms of frequency synthesis may be inexact for precise AM synchronization. If a typical base-2 direct digital synthesizer (DDS) or numerically controlled oscillator (NCO) is used to generate the station's carrier frequency, the frequency step size will be a binary submultiple of the clock frequency. For example, if the clock frequency is 10 MHz and the DDS resolution is 24 bits, then the frequency step size will be approximately 0.596046 hertz.

In this example, if the desired output frequency is 860 kHz, then the closest (decimal) integer value for the DDS would be 1,442,841 and the actual output frequency would be approximately 860,000.2527 hertz. Such a scheme would not achieve correct synchronization. Either the DDS divider would have to be changed to use a base-10 counter, or the DDS would have to be bypassed altogether, or the 10 MHz input would have to be offset in frequency to achieve synchronization.

Alternatively, if the DDS is extended to 32 bits, then a 10 MHz clock results in a step size of about 0.002328 Hz. This level of inaccuracy may be tolerable but not ideal. With a 32-bit DDS and our 860 kHz example the carrier frequency would be about 859,999.998938 Hz, an error of -0.001062 Hz. With a base frequency of 16.777216 MHz (2^{24} Hz) the binary DDS output frequencies can be set to exact 1 Hz increments and will be just as accurate as the usual PLL-based transmitter synthesizers employing a standard 10.000 MHz clock and decade dividers. For more detail on this issue, see [4], [5] and [15].

At the time this document was written, there were no known base-10 DDS chips available; however, it is possible to create a base-10 DDS in modern FPGA chips. Such a base-10 DDS would eliminate all frequency errors of the common binary DDS chips and allow use of the standard 10-MHz reference frequency.

The effectiveness of the synchronization/syntonization concept to reduce AM co-channel carrier-beat interference effects under daytime conditions was demonstrated by Oak Ridge National Laboratory (ORNL) researchers in a laboratory test setup, as described generally in the references and in further detail in Annex A of this document. Many hours of careful subjective listening were conducted, with two interfering AM signals both precisely on-frequency with the main unit (synchronous operation) and with the two interferers at various frequency offsets, from below 1 Hz to above 10 Hz and at a wide range of relative levels.

The most audibly annoying beats were generally judged to be below roughly 2 Hz, so several tests were conducted with offsets of 0.7 and 1.7 Hz, respectively, which tend to more closely emulate current typical AM channel beat characteristics. Subjective measurements to determine the familiar (ISO) audible interference assessment criteria of “imperceptible,” “perceptible,” “annoying,” and “objectionable” were made and documented. Overall, the net effect to the listener of synchronizing the AM carriers and thereby eliminating the beats was on average about 6 dB minimum and was as great as 10 dB. These results are presented graphically in Fig. A1.2, where the effective improvement is represented by the horizontal offset (in dB) between the “Non-Synchronous” and “Synchronous” interference regions. This typical fringe-area daytime scenario can also be of major importance in evening, nighttime, and pre-sunrise listening situations where the signal-to-interference ratio (SIR) due to incoming skywave signals is degraded. (Of course, other test conditions may yield different results). Daytime propagation with ≤ 2 co-channel interferers could extend the interference-limited contours over the non-synchronous case, increasing the station’s coverage area [4] [5] [15].

Although there may be some benefit to having only some stations on a channel synchronized, maximum benefit is obtained if all stations on the channel in question above the noise floor are closely frequency-locked to a common precise reference as just described, or all the beats will not be effectively eliminated. Informal NRSC propagation studies and the NRSC AM co-channel simulator program [11] have shown that even with universal implementation, some stations will benefit appreciably more from carrier synchronization than others, due to the specific co-channel interference profiles present in the coverage area of each facility.

As discussed earlier, some Class C and D stations may experience improved reception areas, with constant equivalent (audible) NIF contours expanded outward due to the reduced carrier-beat levels. The exact coverage benefits of synchronization for a given station can only be ascertained by either physical field testing or through detailed simulations incorporating the actual co-channel interference profile (versus time-of-day [daytime, critical-hours, or nighttime]).

While maximum benefit is only obtained when all the stations above the noise level on a given channel are jointly synchronized to a common frequency reference (e.g., GPS), there can still be benefits to having less than universal synchronization. In some cases, such as on many Class A and B channels, where only 2 or 3 co-channel stations contribute interference D/U ratios above the nighttime RSS noise floor, the potential improvement obtained by joint synchronization can be significant (depending on specific signal levels and modulation density of the desired station). The lab testing described in Annex A, based on this scenario confirms this, as do more recent hardware demonstrations at the 2017 NAB Show.

It is worth noting that a perceptual improvement on the order of just 3 dB is roughly identical to the same increase in coverage that is obtained by doubling transmitted power. At a hardware cost of < $250 (see Section 5.3) and with no increase in the station’s monthly power bill, AM synchronization can potentially provide a great “bang for the buck” for the broadcasters and the listening public.

3.4 Technical Basis

The application of precise carrier-frequency synchronization in AM broadcasting has two principal implementation scenarios: (1) conventional allocations where the co-channel stations are at standard geographic spacings; or (2) where close-in synchronous booster transmitters are deployed in or near the primary coverage area of a local station to provide improved reception in either high-noise or weak-signal areas (e.g., typical of nighttime directional-antenna nulls). As previously mentioned, this Guideline focuses on the first scenario.

Another application of precise carrier frequency-phase control is in wide-area single-frequency networks (SFNs), as already deployed overseas in Great Britain and Japan. It is important to distinguish that in case (1) the phases of the incoming co-channel signals at the receiver are essentially random, whereas in case (2) the phases of the incoming signals are tightly defined by the path delays from each respective transmitter. As previously mentioned, this Guideline focuses on the first scenario, where a tightly defined transmitted carrier phase is not required.

In the first scenario, for standard co-channel situations, only a simple frequency lock (syntonization) is required, without a specifically defined phase characteristic so long as the local carrier phase-change rate is constrained to roughly 10°/minute. This level of stability is easily achieved by most low-cost (i.e., < $250) GPSDO units on the market, which typically employ an inexpensive temperature-compensated crystal oscillator (TCXO) architecture. Higher-cost, higher-performance GPSDO units generally feature an oven-controlled crystal oscillator (OCXO) design using modern stress-compensated (SC)-cut crystals for optimum short-term stability, lower phase noise, and much lower drift. Such units are ideal for the second (close-in) application space, where the RF carrier phase of each transmitter must be tightly controlled to avoid undesirable signal cancellation effects in the overlap reception areas. As noted, these latter applications will not be discussed further in this Guideline but will be reserved for future NRSC documents.

Numerous computer-based modeling studies reviewed by the AIWG, based on the "NRSC AM Co-channel Simulator," written by working group member Dave Hershberger [11], have also confirmed the relatively greater benefits of synchronization for stations with fewer interferers versus the lesser gains achievable in situations involving a multiplicity of interferers. The software provides for extensive customization of the simulations, including specifying the numbers of interferers (from 1 to 71), the specific levels and/or amplitude distributions of the respective interferers, signal phases and frequency errors, fading characteristics, receiver detection and AGC parameters. Outputs of the code include high-resolution synchronous/non-synchronous audio files, received signal spectra, and filtered receiver AGC waveforms to aid in overall performance assessments.

The modeling software has confirmed that for large numbers of interferers, due to the dispersal of the carrier beats due to the large number of randomly-phased co-channel signals, the mitigating effects of synchronization in the receiver are reduced over the cases with just a few interferers. This would indicate that most Class A and B stations will accrue audible benefits at all hours by synchronizing with their co-channel peers, whereas Class C and most Class D stations will similarly gain coverage areas by day but will gradually lose much of the benefit in critical hours and at night, as randomly varying skywave signals increasingly intrude.

For the Class C and D stations during those times, the effective gains in coverage (i.e., audible SIR improvements) will be compressed inward toward the standard NIF contours but should still yield useful gains in coverage. An estimated plot of these effective coverage gains versus the number of effective interferers (above the noise floor) is provided in Figure 1 below. The green contour indicates the typical trend of reception gains due to synchronization, depending also on the actual interference profile and the audible masking of the interference signals by the modulation characteristics of the local (desired) signal.

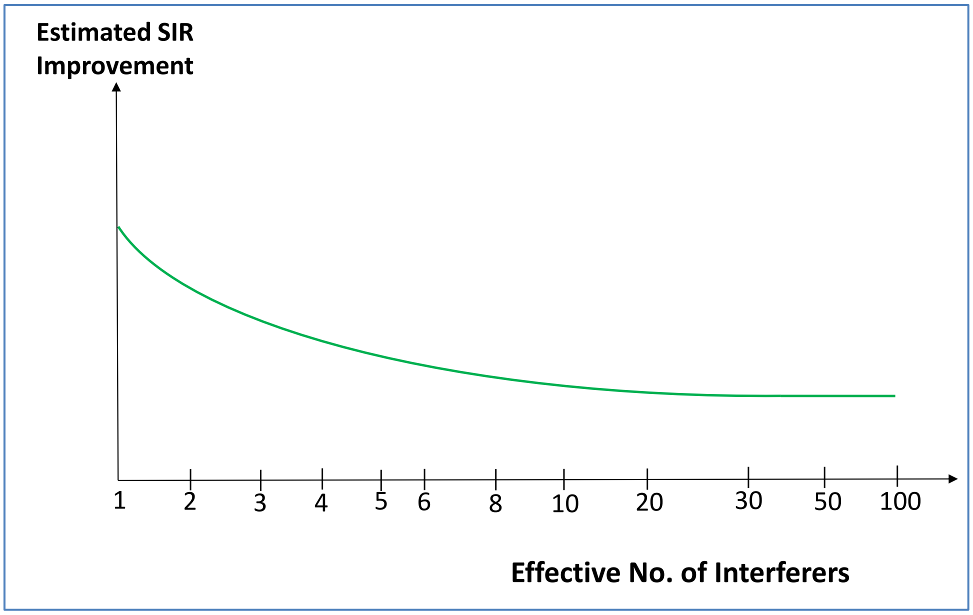

Figure 1. Estimated SIR improvement from synchronization versus no. of Interferers.

More detailed technical assessments of the various considerations of implementing broadcast AM synchronization/syntonization systems are provided in Annex A of this document.

4 REQUIREMENTS

The following paragraphs describe the synchronization/syntonization system technical requirements to comply with this Guideline.

4.1 Phase Noise Measurement Methodology

The phase noise measured using a standard laboratory Phase Noise Test Set (such as the Microchip/Microsemi/Symmetricomm 5120A, Keysight N5511A or E5500, Jackson Labs 53100A, or equivalent) shall be quantified on a clean, unmodulated carrier signal directly obtained from the transmitter at the desired operating frequency, using standard, low-noise, low-drift measurement techniques. Typically, this signal is available from a standard frequency-monitoring port on the transmitter unit and should be properly terminated (normally 50 ohms). The frequency-offset measurement range shall be from 0.01 Hz to 1 kHz, to cover anticipated phase-noise components from 0.01 Hz (10 mHz) into the audible range, nominally through 1-10 kHz.

4.2 Phase Noise Specifications

For the majority of AM synchronization applications, a set of basic frequency-stability parameters for the several stations, generally at nominal geographic spacings, will suffice to ensure the wide-area listener benefits available from synchronization will be realized. These specifications are detailed here:

(1) Individual station frequency errors from nominal: 1 mHz (10^{-3} Hz maximum. Typical GPS-referenced long-term errors are much lower (no more than 1 part in 10^{10}).

(2) Overall transmitted phase noise specifications (in offset from carrier frequency):

(a) To prevent potential CQUAM pilot interference, the sideband noise at ± 25 Hz carrier offsets should be no greater than –54 dBc.

(b) The sideband noise spec with regard to tertiary quadrature information for hybrid IBOC should be –60 dBc or better at ± 181 Hz and above.

(c) To minimize "rumble" caused by the beat of two or more carriers' sideband noise, the minimum spec is –55 dBc at 50 Hz (assuming a typical AM receiver, with keyed AGC and low-frequency audio response).

(3) The minimal dynamic incidental modulation (IPM/QPM) requirements for the transmitter should not be severe: overall, at least –30 dB wideband (100 Hz – 10 kHz), with ≤ 2° IPM/QPM below 100 Hz. Newer units should be able to achieve –40 dB wideband and ≤ 1° IPM/QPM shift below 100 Hz.

(4) The phase noise for a transmitter's standard frequency reference oscillator should fall at a 6dB/octave (20 dB/decade) rate from –55 dB @ 50 Hz offset to about –75 dB at 5-Hz offset in a dB/linear fashion. It should then shelve at –75dBc below 5 Hz. One should be able to measure 5-Hz offset phase noise with lab-grade instrumentation, although with some difficulty. Shot noise may become more of an issue below approximately 10 Hz; again, the –75 dBc spec at 5 Hz offset should be all-inclusive of the multiple noise sources at these low frequencies.

Figure 2 below provides an asymptotic plot, along with a comparative curve of typical noise from a good-quality GPSDO unit such as the Bodnar product mentioned later in this Guideline (see section 5.3). These carrier offset noise and incidental modulation/crosstalk characteristics are generally easily met by well-maintained AM transmitters, even older models, especially those capable of CQUAM use. Units failing to meet these specs often have degraded power-supply filtering and need basic repairs or replacement of filter capacitors; occasionally, defective bypass filtering in the RF chain and/or neutralization failure is responsible.

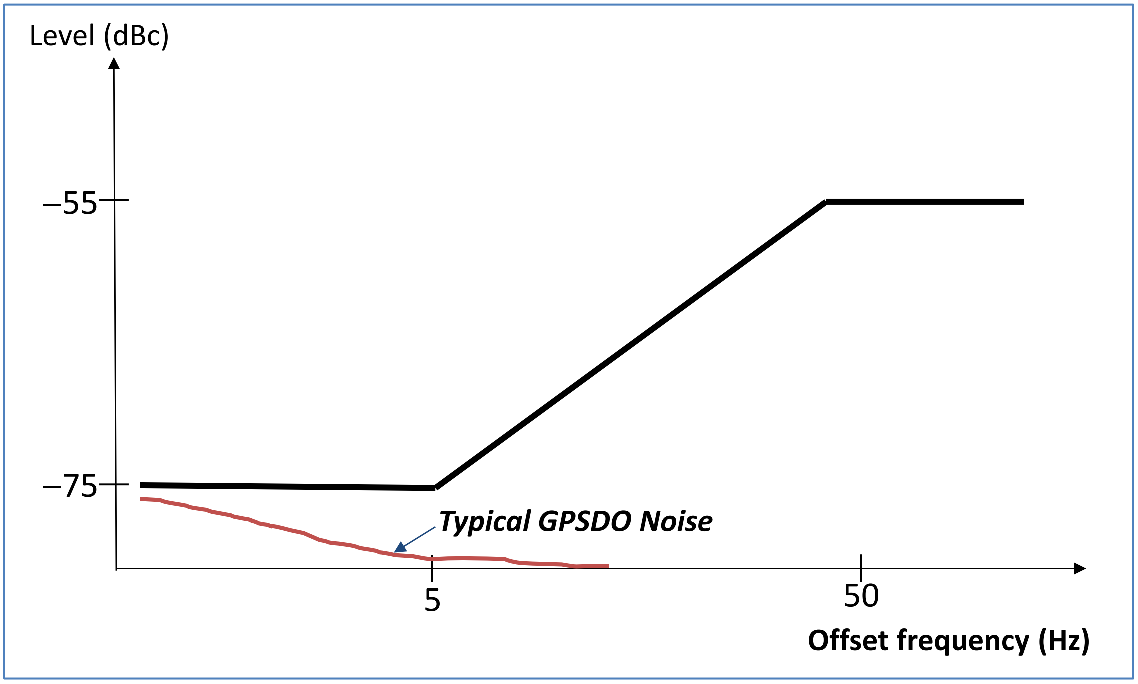

Figure 2. Phase noise requirement for transmitter frequency reference (asymptotic plot).

4.3 Automatic Fall-Back Capability

In the event of operational failure of the synchronized clock system, the broadcast transmitting system should fall back gracefully to operate with a non-synchronous clock. It is generally recommended that detection of a loss of the synchronized signal source automatically restore the transmitter to its original internal oscillator via a simple RF relay or other equivalent means to maintain uninterrupted broadcast transmissions.

Many newer transmitters are designed to accommodate an external frequency reference (typically 10 MHz); if this external reference is lost, the internal oscillator will be automatically selected instead. Older transmitter models, which generally require a reference at 1x, 2x, or 4x carrier frequency, can be straightforwardly interfaced for synchronization by providing the GPS-locked reference at the necessary frequency to either an existing external carrier input (e.g., for C-QUAM or IBOC) or by injection-locking the existing crystal with a simple induction loop around a crystal lead.

Specialized higher-performance commercial GPS-referenced clock units, widely utilized in cell-phone base stations, are often internally configured with a high-stability crystal oscillator which can provide accurate, longer-term frequency holdover when GPS signal lock is lost. Depending on the quality of the internal oscillator, the resulting frequency errors of these units in AM broadcast use would be negligible for holdover intervals of 24 hours or longer, especially for high-quality ovenized SC-cut crystal-based units. Modifications to provide automatic oscillator backup for older transmitters may also require additional sensors and logic circuits to control the RF changeover relays utilized to restore the internal oscillator in the event of synchronizer failure; obviously, these implementations obviously will be highly transmitter-specific.

5 IMPLEMENTATION DETAILS

The implementation of an AM carrier synchronization system depends explicitly on the specific transmitter configuration and on the deployment scenario, either for standard co-channel applications or for close-in synchronous booster use. Exciters in virtually all more modern transmitters have a local high-quality crystal-controlled 10 MHz clock source, followed by a pre-programmed synthesized clock divider to derive the final carrier frequency. These units are typically equipped with external 10 MHz inputs which can be switched via the local control panel to provide the actual transmitting reference frequency; this provides a very easy interface for the GPS-disciplined reference clock, generally with either sinusoidal or square-wave input waveforms. Here, providing proper input waveform voltage and impedance levels for the transmitter at hand are the only major requirements for successful synchronization implementation.

As previously mentioned, exciters in older transmitters are generally equipped with custom-cut but usually somewhat less accurate crystal oscillators, but which may operate at 1x, 2x, or 4x carrier, depending on the specific transmitter architecture. Such older units must generally be interfaced at the specific crystal frequency and using the waveform required by the existing oscillator/buffer electronics. Alternatively, since during the AM stereo era (e.g., CQUAM) most transmitters at that time were provided with an external phase-modulation interface at the nominal carrier frequency, this input could be a straightforward means of introducing an external reference signal for synchronization. For many older transmitters, the specific requirements to implement synchronization are delineated in Annex B.

At present, several integrated GPS-disciplined oscillator (GPSDO) modules are available on the commercial market for around $200. These generally contain a master 10 MHz oscillator, along with a downstream digitally programmable synthesizer/divider to generate one or two additional user-defined frequencies, which can be used to feed older transmitters which are not equipped with internal frequency synthesizers for carrier generation. Some older transmitters (mostly tube-type units) may also require an auxiliary RF power amplifier and/or a step-up RF transformer (tuned or untuned as needed) to produce the higher voltage levels required to properly drive the RF chain in these older units.

5.1 Exciters with Integrated 10-MHz Oscillator Capability

The vast majority of modern AM transmitters (less than 30 years old) rely on a master 10-MHz oscillator and downstream RF frequency synthesizer and/or phase-locked loop (PLL) architecture to generate the final carrier frequency. Most of these transmitters also provide an auxiliary 10-MHz reference input for an external synchronization signal, generally with a sinusoidal or square waveform of 1–5 volt P-P level. Such units can be easily provided an external 10 MHz signal to synchronize the carrier frequency to the atomic-standard accuracy of the GPS system, typically from a low-cost GPSDO unit as mentioned above and detailed in later section of this document. A comprehensive listing of these transmitters, including specific interfacing requirements, is provided in Appendix B of this Guideline. The 10-MHz reference signal is generally routed to the transmitter via a standard 50-ohm coaxial cable and in virtually all cases should be properly terminated, either via the transmitter input circuitry or an external coaxial terminator.

5.2 Older Exciters with Custom Crystal-Controlled Oscillators

Older transmitters, including earlier solid-state units, generally were implemented with specific custom-frequency crystal-based internal oscillators. Often these oscillators could be bypassed via internal wire jumpers, such as were commonly done when adding AM stereo (CQUAM) modulation to the unit. As above, the solid-state units typically required on the order of 1-5 volt RMS drive signals, while the older tube-type transmitters generally required much higher drive levels (though at higher impedance) to properly substitute for the original internal oscillator and/or following buffer stage. As above, for the benefit of station engineering personnel, these transmitters are also listed in Appendix B, along with their specific interface parameters. Most older transmitters can be successfully synchronized using the same general techniques developed for interfacing external AM stereo exciters (i.e., supplying an external carrier-frequency reference signal into the transmitter's RF chain). For those models not listed or for more information, the transmitter manufacturer's customer-service personnel or a consulting engineer should be consulted to determine appropriate interfacing circuitry, signal levels, and setup procedures. It should be noted that relatively few older units incorporate automatic fallback provisions to revert to the original internal oscillator in the event of an external-reference failure. If absolutely required, this function can be added via a simple RF sensor circuit driving an automatic changeover relay to switch back to the internal (or standby) oscillator in the event of reference loss. With most GPSDO units (including the suggested low-cost Leo Bodnar unit), even if GPS sync is lost, the onboard 10 MHz TCXO or OCXO signal will continue, just without the extreme accuracy (~ 1 part in 10^{11}) provided by the satellite ensemble. In any event, the AM transmitter will normally stay on the air without interruption.

5.3 Example Low-Cost GPSDO Unit for AM Syntonization Use

A typical low-cost GPSDO-based unit is the “Precision GPS Reference Clock” unit from Leo Bodnar Electronics in the U.K.[1] The basic block diagram is shown below in Figure 3. The standard system (including patch-type GPS antenna) is (as of August 2023) priced at £165 ($234 U.S.) and is widely used in amateur radio systems worldwide. The unit is fully computer-programmable using a one-time standard Windows application via a USB link and can generate either a 10-MHz signal for use with newer transmitters or specific carrier frequencies for interfacing older transmitters.

A standard analog +5 volt supply is required for the Bodnar unit itself. The level from both synthesizer outputs (sine or square wave) at 10 MHz or below is about +13 dBm or 2.8 V P-P into 50 Ω and can be AC-coupled into many modern transmitter reference inputs directly. Others may require somewhat greater drive levels, which can be obtained by inserting a simple amplifier/comparator circuit between the GPSDO and the transmitter carrier input, as discussed in section 5.4.

Older transmitters, including tube units, will usually require a linear RF booster power amplifier, such as the Mini-Circuits ZHL-3A+ or ZHL-32A+ and a compatible power supply (normally analog 24-V DC). Examples of both interfaces are provided in section 5.4. The Bodnar unit is shipped with a standard magnetic-mount GPS patch antenna, but a premium high-gain, SAW-filtered timing antenna is also available for situations where due to high ambient RF noise GPS signals could suffer interference. If the GPS signals at a given site are subject to occasional interference or loss, the holdover spec becomes important. After about an hour of GPS loss, the TCXO-based Bodnar unit may not be able to permit the transmitter to maintain the legal ±20 Hz frequency tolerance, so it is recommended that the station provide a remote-control alarm interface in case GPS unlock is detected.

Although the Bodnar unit does not provide time and location solutions as do many more costly GPSDO models, it still provides extremely high-accuracy, low-drift frequency outputs and is entirely satisfactory for the basic co-channel AM syntonization function of eliminating carrier-beat effects and improving coverage. Its low cost, reliability, and straightforward implementation will fully support the needs of cash-tight AM operations and provide the full benefits of co-channel synchronization to the users.

The overall performance of the unit is excellent, with the phase noise spectrum comfortably below the system reference requirements specified in Section 4.1 (also as in Figure 2) of this Guideline. This unit is equipped with a high-quality TCXO, which is suitably stable for this application. Higher-performance GPSDO units are available from other vendors (i.e., Trimble, NEL, Garmin, uBlox, Collins, Systron-Donner, Jackson Labs, etc.) with much more stable OCXO, Rubidium, or even chip-scale atomic clock (CSAC) embedded oscillators for lower phase noise, drift, and much longer holdup times, but at considerably higher cost and greater power consumption figures.

The basic performance specs of the Bodnar Precision GPS Clock unit are as follows:

Basic frequency accuracy – better than 1 part in 10^{11}

Allan Variance $\sigma_y(\tau)$:
τ=1 s: 5.13 ×10^{-11}

[1] See https://www.leobodnar.com/shop/index.php?main_page=product_info&products_id=234. Available in the US at https://v3.airspy.us/product/lb-gpsdo-mini/.

τ=10 s: 2.03 $\times 10^{-11}$
τ=100 s: 3.09 $\times 10^{-12}$
τ=1000 s: 7.81 $\times 10^{-13}$

Measured phase noise of GPS clock at 10 MHz output is equal or better than -70 dBc/Hz at 1 Hz offset from the carrier:
-100 dBc/Hz at 10 Hz
-125 dBc/Hz at 100 Hz
-143 dBc/Hz at 1 kHz
-150 dBc/Hz at 10 kHz
-152 dBc/Hz at 100 kHz
-155 dBc/Hz at 1 MHz

Output level at ≤10 MHz (both outputs): +13.3 dBm into 50Ω maximum (adjustable).

Holdover: 60 minutes with loss of GPS (nominal).

Synthesizer: Silicon Labs Si5328 chip.

GPS Antennas: Patch (standard), Timing "Bullet" antenna with 10-m or 30-m cable (optional).

Power requirement: 5 – 12 V DC @ 250 mA; also USB @ 250 mA.

Enclosure: Shielded, metal, with external SMA antenna and BNC output connectors

Website: www.leobodnar.com

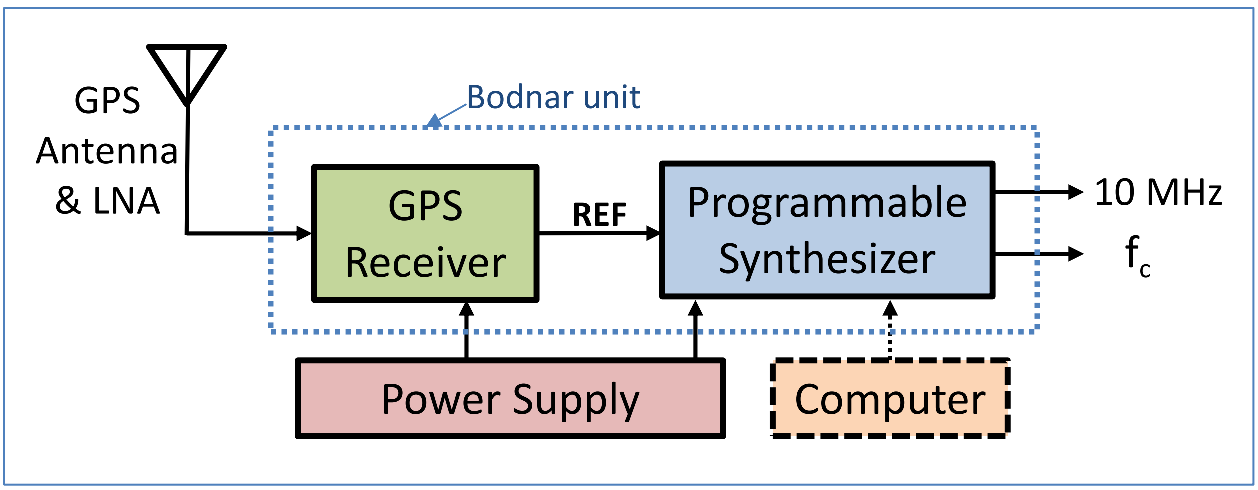

Figure 3. Block diagram of typical low-cost GPSDO system (Leo Bodnar "Precision GPS Reference Clock").

5.4 Typical Booster Interfaces for Older Transmitters

To secure adequate drive levels from the Bodnar and similar GPSDO units, two types of interface circuits are typically employed. For older solid-state transmitters with either sinusoidal or square wave drive requirements, a simple comparator-type amplifier providing at least a ±5-volt P-P output is usually adequate, as shown in Figure 4 below.

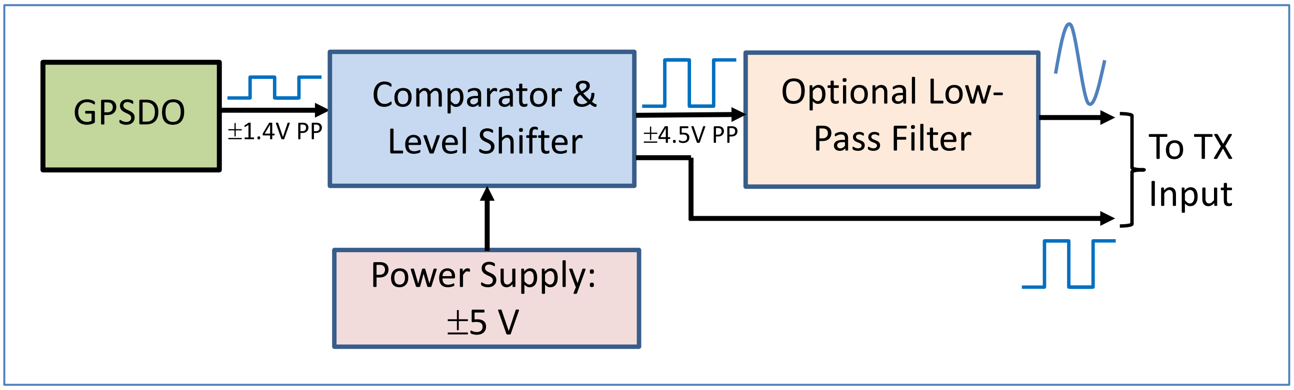

Figure 4. Block diagram of typical GPSDO unit with comparator-type booster.

For much older tube-type models, a linear RF power amplifier is often necessary to obtain sufficient power and voltage swing to properly drive these legacy units (often as much as 30 volts P-P, which may further require an external RF step-up transformer). A representative setup of this type of booster is illustrated in Figure 5. Note that an external 24-volt DC power supply is needed to provide the necessary signal amplitudes in this case. Typical signal levels are also indicated in the diagrams.

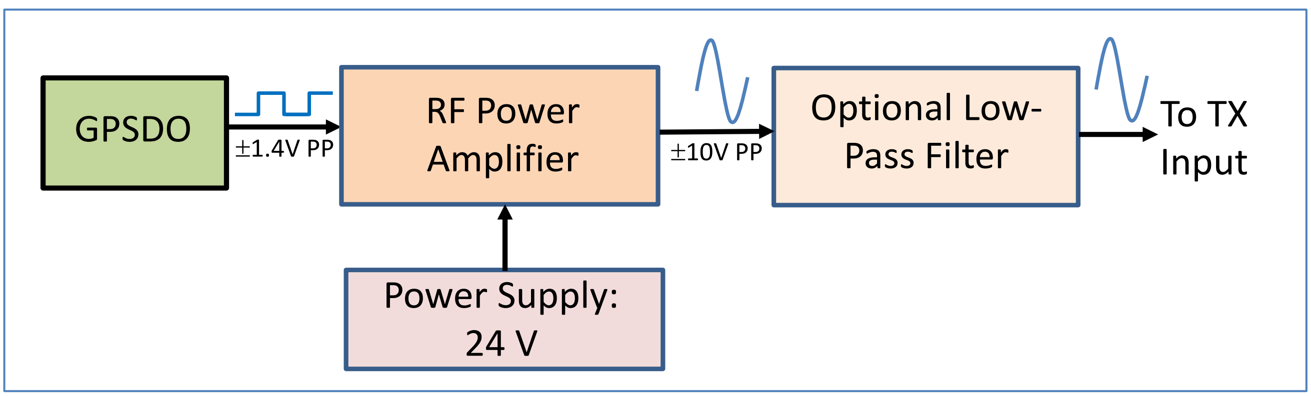

Figure 5. Block diagram of typical GPSDO unit with RF power amplifier booster.

ANNEX A: ANALYSIS OF AM CARRIER FREQUENCY SYNCHRONIZATION

AM Carrier Synchronization Lab Testing

Referring to Figure A1.1, the effectiveness of the synchronization concept for AM broadcasting was initially demonstrated with a laboratory test setup at Oak Ridge National Laboratory in Oak Ridge, TN during the 2000-2003 time frame. To receive local-area broadcast signals as convenient multiple peak-limited audio sources, an external rooftop FM antenna was connected to a 3-way splitter, which in turn fed three different component FM broadcast tuners. Each of the tuners, tuned to a different local station, was coupled to an individual audio level-adjust amp and thence to an externally modulated frequency-synthesized AM signal generator.

A low-frequency function generator was also employed to phase-modulate one of the signal generators to simulate nighttime skywave signal fading. The “main” signal generator was directly coupled to a 3-way combiner, while the other two “interfering” signal generators were each coupled to the 3-way combiner via a variable attenuator. The output of the 3-way combiner was fed to a high-quality AM tuner via a fixed attenuator; the tuner then fed the lab loudspeakers via a commercial component-grade high-power stereo audio receiver used as a monitor amplifier. This setup provides for a local signal and 2 variable-amplitude interferers.

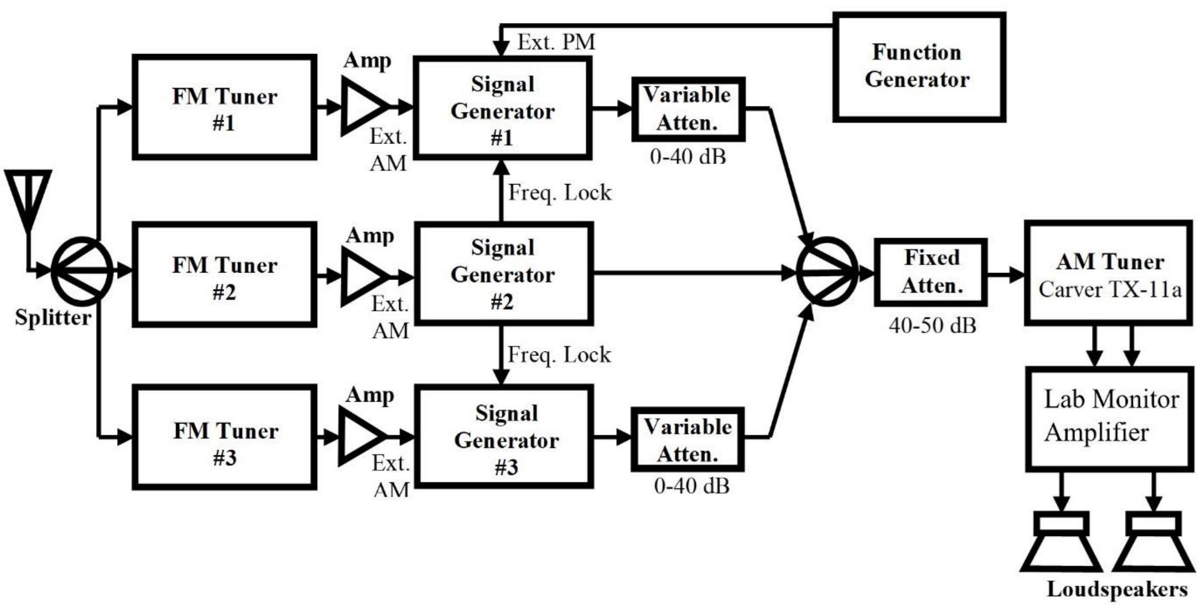

Figure A1.1. Laboratory AM Synchronization Testing Setup.

Still referring to Figure A1.1, the laboratory test setup employed three signal generators which could be externally modulated. The “B” channel of a high-performance synthesized two-channel signal generator, a Hewlett-Packard model 3326A, was used as the reference (“local”) AM station; the “A” side was set up as one of two “interfering” co-channel stations. The other “interferer” was simulated by a separate single-channel synthesized HP 3325B generator. All three generator units were commonly locked to a high-stability ovenized 10.000 MHz clock within the 3326A chassis.

For the test, all units were nominally set to 1000 kHz, as was the high-quality Carver TX-11a audiophile AM Stereo/FM Stereo tuner which was used to demodulate the combined signals and feed the external monitoring amplifier/speaker system in the lab. The generator outputs were all set at a nominal 0-dBm output level (50 ohms) and fed to a three-input passive 0° RF power combiner (a Mini-Circuits Labs type ZSC-4-1). The combiner's 50-Ω output was attenuated about 40-50 dB before being fed to the RF antenna input of the high-quality tuner, which itself was terminated and de-sensitized by a 50-Ω resistor.

Initially lacking equipment to generate FCC-standard C-QUAM AM stereo signals, the interference tests were all conducted with standard monaural audio modulation, although some subsequent trials included the "main" signal operated in C-QUAM stereo to test the overall effect of synchronization on stereo reception. Three consumer-grade FM broadcast tuners were set to three different area stations to obtain reasonably clean, peak-limited audio sources to modulate the three AM generators via their external-AM audio inputs. The main generator was fed directly to the AM signal combiner, while each of the two "interferers" was connected through a pair of switchable step attenuators, one with 10 dB steps and the other with 1 dB increments.

Many hours of careful subjective listening were conducted, with the two interfering units both precisely on-frequency with the main unit (synchronous operation) and with the two interferers at various frequency offsets, from below 1 Hz to above 10 Hz. The most audibly annoying beats were generally judged to be below roughly 2 Hz, so several tests were conducted with offsets of 0.7 and 1.7 Hz, respectively, which tend to more closely emulate current typical AM broadcast co-channel beat characteristics.

Referring to Figure A1.2, subjective measurements to determine the familiar audible interference assessment criteria of "imperceptible", "perceptible", "annoying", and "objectionable" were made and documented. An extra sub-category within the "perceptible" bracket, denoted "long-term-listenable" ("slightly perceptible"), was added to assist in delineating a listening quality level adequate to avoid "tune-outs" caused by carrier beats and other background interference.

For this test campaign, impulse noises such as from lightning were deemed out of the scope of this effort and were therefore not included. To help simulate significant nighttime ionospheric phase/propagation-delay shifts, in both synchronous and non-synchronous scenarios, an auxiliary low-frequency function generator was added to externally phase-modulate the larger interferer's signal at rates varying from 0.5 Hz to below 0.01 Hz (a 100-second period); the usual periods of fading were from 10 to 30 seconds, following past experience of the researchers.

Obviously, the interference in the standard (non-synchronous) case consisted of both carrier beats and background co-channel audio modulations, while in the synchronous setup the beats were absent. At low signal-to-interference ratios (SIRs), i.e., below about 12 dB, the non-synchronized beats were highly annoying and caused gross intermodulation of the received audio program. At much higher SIRs, approaching 30 dB, even the non-synchronized beats became imperceptible to most listeners. At intermediate SIR levels (~12-20 dB), the effects were strongly dependent on the exact nature of the three audio modulation signals, due to masking of lower-level sounds by louder concurrent ones in the human auditory system.

Slightly different results were therefore obtained for fast ("pop") to slow music [M], average voice [V], fast-paced voice [FV] (e.g., commercial advertisements) and slow-tempo voice [SV] (e.g., telephone-talk shows). Overall, the net advantage to the listener of synchronizing the AM carriers and thereby eliminating the beats was on average about 6-dB minimum and was as great as 10 dB; this is of major importance in evening and nighttime situations where the SIR due to incoming skywave signals can degrade to levels of 12 dB or worse.

Thus, for comparable audibility, with synchronization, interfering signals from co-channel stations could be from 6 to 10 dB higher than in the current non-synchronized scenario (less at night). The net result was that a listener may be at a position where the SIR is 6-10 dB worse (i.e., at roughly twice to three times the distance from the desired station) before the interference becomes annoying, as compared with the present situation. Even at an 8-dB SIR, when the carrier beats from unsynchronized stations were extremely objectionable, interference from well-synchronized remote signals was masked surprisingly well by bright, highly modulated audio from the stronger ("local") station and thus rendered a reasonably listenable signal.

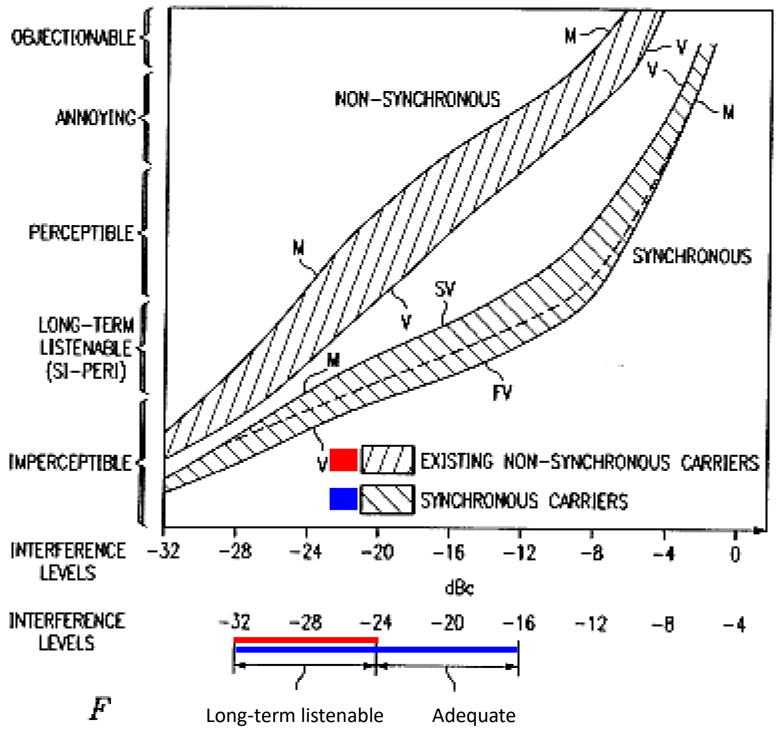

Figure A1.2. Audibility of Synchronous vs. Non-Synchronous Interference (2 Interferers) [4].

Field Benefits of Universal Synchronization

The standard nighttime interference-free (NIF) contour for each station is defined as the line where the groundwave signal of the desired station is 26 dB above the aggregate (RSS) co-channel RF skywave interference level, effectively equivalent to the statutory 26 dB co-channel daytime protection specification. It is instructive to note that on many Class-C channels the aggregate co-channel nighttime interference level is actually in the range of 1 –1.25 mV/m [12], which limits the NIF contours of such stations to just a few (<10) miles from the transmitter (i.e., where the local groundwave signal is 20 – 25 mV/m).

For example, currently a Class C station operating with 1 kW into a full half-wave tower, with a local ground conductivity of 6-15 mS/m, will exhibit a conventional (26-dB) NIF radius of roughly 7-9 miles, respectively. With full carrier synchronization on the channel, the equivalent NIF radii (23 dB/20 dB SIR) would increase to about 9-12 miles (3-dB typical gain) and up to 11-14 miles (6-dB optimum gain using high average modulation on the local station to help mask the incoming skywave signals). This results in at least a doubling of the equivalent (i.e., equal audible SIR) coverage area for the station, both during daytime, critical hours, and at night.

Synchronous AM Doppler Effects in Mobile Receivers

Referring to Figure A1.3, hypothetical field contours of two overlapping equal-power synchronous (co-channel) AM transmitters are depicted with various mobile-receiver trajectories. For a listener traveling in a path connecting two 1.0 MHz transmitters at a constant velocity of 30 m/s (about 67 mph), as shown on trajectory V_1 of Figure A1.3, these signal minima will appear at an interval of (150 m) ÷ (30 m/s) = 5 s, or at a rate of 0.2 Hz.

For the typical automobile AM radio receiver with an effective automatic gain-control (AGC) loop bandwidth of roughly 5 to 10 Hz, this 0.2-Hz variation will be easily leveled out by the AGC loop so long as there is sufficient residual gain in the receiver to amplify the resultant signal at these partial null-points. For velocity vectors at other angles from the transmitters, the standing-wave amplitude-oscillation intervals will be longer by a factor of the inverse of the cosine of the angle from the direct or radial path; for instance, if the path is at 45° from the radial, the oscillation period will be (5 s) ÷ (cos 45°) = 5/0.707 = 7.07 s.

For example, on trajectory V_2 of Figure A1.3, the receiver is moving tangentially with respect to Station 1 but radially toward Station 2. Thus, there will be no relative shift in the receiver from signal 1, but the maximum Doppler-frequency shift (for that velocity) of +0.1 Hz will be observed for signal 2. For paths which are neither tangential or radial to either transmitter, such as V_3 of Figure A1.3, both shifts will be present but will be of intermediate frequencies (i.e., $|f_{beat}| < 0.1$ Hz). For velocity paths essentially perpendicular to the radial (cos 90° = 0), as on path V_4, the oscillations will be of very long periods and of vanishing amplitudes.

Although theoretically there will be cancellation nulls of great depth at many discrete points in the field of the two transmitters, in reality the nulls will only be partial, due to local variations in the amplitude and phase of the transmitted ground waves, scattering effects, and diffraction over hills and other large terrain features. If the receiver gain range is sufficient to compensate for a null depth of about 20-30 dB worst case, the audible effects will usually be modest, except in the nearly-equal signal zones (pinkish areas). In this case, when the synchronous stations' modulation is properly time-synchronized (to within about 0.1 μs), as documented in [4] [15], the potential interference zones shrink to the much smaller areas shown as purplish-pink crescents at the center. Even in these zones, the signal interferences in actual field settings resemble typical FM multipath effects in a mobile receiver, and are thus not overly noticed by typical listeners [4] [15].

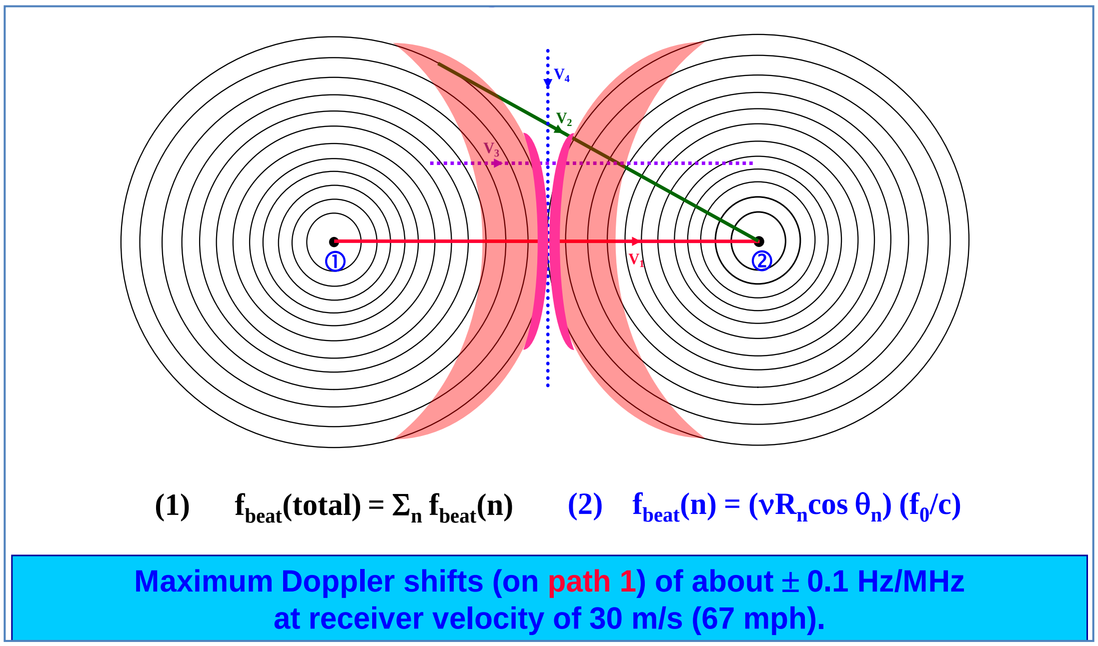

Figure A1.3. Plot Illustrating Doppler Effects in Mobile Receivers for Synchronous Stations 1 & 2.

Another way of describing this effect is that of Doppler-induced carrier-frequency shifts in moving (vehicle) receivers. For the aforementioned scenario, where a vehicle is moving at 30 m/s on a linear path between two frequency-locked stations (path V_1) at 1.0 MHz, the apparent frequency of the transmitter being approached will be shifted *upward* by $(3 \times 10^1$ m/s$) \div (3 \times 10^8$ m/s$) \times (10^6$ Hz$) = 0.1$ Hz, while the transmitter being receded from will exhibit an apparent *downward* shift of 0.1 Hz. The net result will be an observed offset of 0.2 Hz between the two carriers, with the attendant beat. The effective beat frequency with respect to each station will thus be a function of the product of vehicle speed, the cosine of the velocity-vector angle with the radial from the station, and the true transmitted RF carrier frequency.

Equivalently, the Doppler shift from each station (1 or 2) is the product of the radial component of the relative vehicle velocity (referred to the specific transmitter) and the carrier frequency, divided by the speed of light (or RF) in the atmosphere over the terrain. The total composite beat frequency is simply the sum of the two Doppler shifts (for both 1 and 2). In general, the path on the common radial will produce the worst-case (highest) beat frequency; ideally, a path perpendicular to that line will produce no beats, since the Doppler shifts of each station will be equal in magnitude *and* sign and thus cancel at the moving receiver. The mathematical equations are thus:

$$(1) \qquad f_{beat(total)} = \Sigma_n \, f_{beat(n)}$$

$$(2) \qquad f_{beat(n)} = (\nu_{Rn} \cos \theta_n)\,(f_0/c)$$

where $f_{beat(n)}$ is the nth beat frequency in Hz, ν_{Rn} is the 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 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.

Obviously, the magnitude 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 6 dB different in level, the resultant beats are very weak. Compared with the standard static-receiver synchronous AM reception case discussed previously, the presence of these sub-Hertz beats in *mobile* listening environments typically causes a degradation (i.e., increase) in the overall beat audibility of only about 1-1.5 dB compared with the curves in Fig. A1.2. 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.

In static conditions, as in Figure A1.3, where cancellations due to carrier out-phasing are deeper, the regions of higher distortion are shown in light pink (only the smaller purple areas if audio delay-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, and inaudible in typical vehicles.

Summary and 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 (< $250) GPS timing receivers and inexpensive electronic devices such as microprocessors and logic chips. *We anticipate that for a maximum cost between $1-2K, a GPS-referenced frequency-synchronizer unit can be easily deployed at existing 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. Although most newer transmitters can be readily interfaced with logic-level reference signals, some older (mostly tube-type) units will require additional RF power-booster amplifiers to properly interface the reference carrier signal into the unit's signal chain.

According to our limited lab and field tests, the net result of universal AM carrier-frequency synchronization could be an increase of the existing co-channel interference-limited daytime coverage radius of most stations (and thus of the serviceable reception area). For most Class C & D broadcasters, the gains would usually be noticeably less due to their much higher numbers of significant interferers during critical hours and at night. It is significant to note that most all Class C stations at 1 kW currently suffer 6 dB more daytime co-channel interference than is standard (for Classes B and D) since they are only equivalently protected to their 1.0 mV/m contours from other Class C signals. Thus they are already subject to more overlap than Class A, B, and D stations and should benefit even more from wide-scale carrier synchronization.

Perspectives

The relatively low installed cost (≤ $1K) of a GPS-based AM synchronization system would seem to be a good investment, particularly when weighed against the coverage gains to be realized. Overall, AM synchronization is an easily deployed technology that could in many situations provide stations coverage gains at relatively low cost. Factors that affect the benefits realized include the number and proximity of co-channel stations and time of day (for example, more improvement is expected during critical hours).

ANNEX B - INTERFACE REQUIREMENTS FOR SPECIFIC AM TRANSMITTERS

Table of AM Transmitters and Interface Parameters

The following table lists common AM transmitter models, both from current manufacturers and many types of widely-used legacy units. Pertinent interface parameters required to implement effective carrier-frequency synchronization are listed, including: (1) Waveform (sine/square wave); (2) External reference frequency (either carrier or 10 MHz); (3) Peak-to-peak voltage levels; (4) nominal impedance (typically 50 ohms or high impedance, as with a 1:2 step-up RF transformer used with many tube units); and (5) built-in automatic fallback, in case of a total loss of the external reference signal. This feature assures no loss of airtime, with a smooth transition to an internal reference signal, when the external reference fails.

Transmitter Mfg./Model	Waveform	Ext. Ref. Frequency	Voltage (P-P) (Min/Max)	Impedance (Ω)	Auto Fallback
GatesAir/Harris/Gates					
SX Series	∿/⎍	f_c	4-5	50/10K	No
MW Series	∿/⎍	f_c	4-5	50	No
DAX-1 – DAX-6	∿/⎍	10 MHz	2-20	50/10K	No
DX-10/15	⎍	f_c	4-5	50/20K	No
3DX25/50	∿/⎍	10 MHz	4-5	50/10K	No
BC-1H	∿	f_c	23	1:2 Transf.	No
BC-1G	∿	f_c	23	1:2 Transf.	No
BC-1F	∿	f_c	23	1:2 Transf.	No
BC-5H	∿	f_c	23	1:2 Transf.	No
BC-5P2	∿	f_c	30	1:2 Transf.	No
Nautel					
AMPFET 1/2.5/5/10	∿/⎍	f_c	2.8-8.4	56	No
AMPFET 25/50	∿	f_c	2.8-8.4	56	No
P400	∿/⎍	f_c	2.8-8.4	56	No
ND 1/5	∿/⎍	f_c	5.0-12.0	50	No
ND 5, Mk. I	∿	f_c	2.8-8.4	50	No
ND 5, Mk. II	∿/⎍	f_c	5.0-12.0	50	No
ND 10, Mk. I	∿	f_c	2.1-4.2	50	No
ND 10, Mk. II	∿/⎍	f_c	5.0-12.0	50	No
ND 25/50	∿/⎍	f_c	5.0-12.0	50	No
J1000	∿/⎍	f_c/10 MHz	5-12/2.2-8.0	4.1k/50	No
XL12, 30, 60	∿/⎍	f_c	5.0-12.0	50	No
XR3, 12, 25, 50	∿/⎍	f_c/10 MHz	5-12/2.2-8.0	4.1k/50	No
NX3, 5, 10, 15, 25, 50	∿/⎍	10 MHz	2.2-8.0	50	Yes

Transmitter Mfg./Model	Waveform	Ext. Ref. Frequency	Voltage (P-P) (Min/Max)	Impedance (Ω)	Auto Fallback
Continental/Collins					
Continental 316-F	∿	f_c	?	50	No
Collins 20V3	∿	f_c	23	1:2 Transf.	No
Collins 21M	∿	f_c	23	1:2 Transf.	No
Collins 820D1	∿	f_c	25	50	No
Collins 820D2	∿	f_c	8	50	No
Collins 820E/F1	∿	f_c	30	1:2 Transf.	No
Collins 828C1/Cont. 314R-1	∿	f_c	?	?	No
Broadcast Electronics					
BE AM-500A, 1A, 6A, 10A	∿/⎍	f_c	5-15	3.4k	No
BE AM-1, 2.5, 5, 10	∿/⎍	f_c	5-15	3.4k	No
RCA					
BTA-1R1	∿	f_c	33	1:2 Transf.	No
BTA-5L1	∿	f_c	4-5	50	No
BTA-5L2	∿	f_c	2-20	50	No
BTA-5T1	∿	f_c	4-5	50	No
BTA-5SS	∿	f_c	4-5	50	No
Other Manufacturers					
GE BT-50-A	∿	fc	30	1:2 Transf.	No
CCA AM 10,000	∿	fc	33	1:2 Transf.	No
Elcom Bauer 705C	∿	fc	4	50	No
Sparta Bauer 707	∿	fc	?	?	No
McMartin BA-1K/2.5K	∿	fc	4-5	50	No
McMartin BA-10K	∿/⎍	fc	4-5	?	No
Raytheon RA-1000	∿	fc	23	1:2 Transf.	No

This table has been assembled from data made available to the NRSC by the various transmitter manufacturers and from Consulting Engineers, particularly for legacy units not now supported by their original manufacturers. Many of the older models can be successfully interfaced for synchronization purposes using an external carrier input generally intended to implement AM stereo modulations, as shown in Annex C. Unknown or doubtful parameters are denoted by a question mark and must be determined by the station. For specific synchronization implementation parameters and issues not clarified in the above table, including models not listed and general GPS reception issues, station technical personnel are strongly encouraged to contact Customer Support at the respective transmitter's manufacturer and/or a qualified Consulting Engineer for assistance.

ANNEX C - MODIFICATIONS TO LEGACY AM TRANSMITTERS FOR C-QUAM

The Motorola C-QUAM AM stereo system was adopted as a standard by the FCC in the 1990s. Modifications to legacy equipment were often necessary to accommodate C-QUAM, and the NRSC has obtained schematic diagrams showing proposed modifications to specific transmitter implementations to allow for use of C-QUAM, which are included in this Annex.

This information is being provided for reference only and these modifications have not been tested by the NRSC, though they were implemented in the field some years ago by consulting engineers who are currently NRSC members. They may be applicable to transmitter modifications needed to support carrier synchronization.

Page	Manufacturer	Model
C-2	CCA	AM 10,000
C-3	Collins	20V-3
C-4	Collins	21M
C-5	Collins	820D-1
C-6	Collins	820D-2
C-7	Collins	820E/F-1
C-8	Collins	828 C-1
C-8	Continental	314 R-1
C-9	Continental	316-F
C-10	Elcom/Bauer	705C
C-11	Gates	BC-1F
C-12	Gates	BC-1G
C-13	Gates	BC-1H
C-14	Gates	BC-5P2
C-15	Gates Harris	BC-5H

Page	Manufacturer	Model
C-16	GE	BT-50-A
C-17	Harris	MW-1/1A
C-18	Harris	MW-5/5A
C-19	Harris	SX5
C-20	McMartin	BA-1K, 2.5K
C-21	McMartin	BA-10K
C-22	Nautel	AMPFET 1-50 kW
C-23	Raytheon	RA-1000
C-24	RCA	BTA 5SS
C-25	RCA	BTA-1R1
C-26	RCA	BTA-5L-1
C-27	RCA	BTA-5L-2
C-28	RCA	BTA-5T1
C-29	Sparta Bauer	Type 707

NRSC Document Improvement Proposal

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