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GUIDELINE

NATIONAL RADIO SYSTEMS COMMITTEE

NRSC-G201

NRSC-5 RF Mask Compliance: Measurement Methods and Practice

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FOREWORD

The NRSC-5 in-band/on-channel (IBOC) Digital Radio Broadcasting Standard specifies IBOC systems for both the AM and FM bands, including detailed specification of the parameters which must be met by the radio frequency (RF) signal which is ultimately broadcast by an IBOC facility. The most common graphical expression of some of these parameters is the so-called "RF mask" which can be thought of as a template within which the IBOC RF signal must fit.

Given the variety of transmission facility configurations suitable for IBOC signal generation as well as the need to characterize IBOC RF signals by both equipment manufacturers (during construction and testing of IBOC transmission equipment) and broadcasters, various methods must be utilized to determine whether an RF signal is compliant with the RF masks specified by NRSC-5. The purpose of the NRSC Guideline is to provide background information as well as detailed instructions on the best methods and practices for determining RF mask compliance for the situations most likely to be encountered by equipment manufacturers and broadcasters.

The information contained in this NRSC Guideline is the work of the IBOC Standards Development Working Group (ISDWG), a subgroup of the Digital Radio Broadcasting (DRB) Subcommittee of the NRSC. At the time of first adoption of this Guideline, the ISDWG was chaired by Dom Bordonaro, Cox Radio, and the DRB Subcommittee was co-chaired by Mike Bergman, Kenwood, Americas Corporation, and Andy Laird, Journal Broadcast Group. The NRSC chairman at the time of adoption of NRSC-G201 was Milford Smith, Greater Media, Inc.

The NRSC is jointly sponsored by the Consumer Electronics 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.

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1 SCOPE

This is an informative Guideline document which sets forth recommended methods and practices for determining if hybrid FM and AM IBOC digital radio transmissions fall within the RF masks specified in the NRSC-5 Standard. While not dealt with explicitly, the information on hybrid FM IBOC signals applies to extended hybrid FM IBOC signals, as well. The NRSC anticipates incorporating information pertaining to all-digital IBOC transmissions (as specified by NRSC-5) at the time when such transmissions are authorized by the Federal Communications Commission (FCC).

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 editions indicated were valid. All standards are subject to revision, and users of this Guideline document are encouraged to investigate the possibility of applying the most recent editions of the standards listed below.

[1] *NRSC-5-B In-band/on-channel Digital Radio Broadcasting Standard*, National Radio Systems Committee, April 2008

[2] *NRSC-2-A Emission Limitation for Analog AM Broadcast Transmission*, National Radio Systems Committee, September 2007

[3] *Code of Federal Regulations (CFR) 47, Part 73, Subpart C – Digital Audio Broadcasting*, Office of the Federal Register, National Archives and Records Administration

[4] *HD Radio Implementation*, Thomas R. Ray, Focal Press, 2008

[5] *The IBOC Handbook: Understanding HD Radio Technology*, David P. Maxson, Focal Press, 2007

[6] *The NAB Engineering Handbook, 10th Edition*, Edmund A. Williams, Editor-in-chief, Focal Press, 2007

[7] The *Role of the Detector in Spectrum Analyzer Measurement of Hybrid Digital Signals*, David P. Maxson, pp. 397-404, 2008 NAB Broadcast Engineering Conference Proceedings

[8] *Isolation in FM IBOC Multi-Channel Systems-St. Louis, Real World Data*, Henry Downs, pp. 41-46, 2007 NAB Broadcast Engineering Conference Proceedings

[9] *Rebuilding a Legend: Rebuilding WOR Radio from the Tip of the Mic to the Top of the Tower*, Thomas R. Ray, pp. 243-264, 2007 NAB Broadcast Engineering Conference Proceedings

[10] *Beyond Spectral Occupancy: an Investigation of IBOC Signal Quality Metrics*, David P. Maxson, pp.345-352, 2006 NAB Broadcast Engineering Conference Proceedings

[11] *Transmitter Output Power Measurements in Digital Broadcast Systems*, Tim Holt, pp. 361-366, 2006 NAB Broadcast Engineering Conference Proceedings

[12] *Improvements to FM and IBOC Signal Quality through the Use of Pre-equalization*, Mike Woods, pp. 391-396, 2006 NAB Broadcast Engineering Conference Proceedings

[13] *8 Hints for Better Spectrum Analysis*, Application Note 1286-1, Agilent Technologies March 27, 2008

[14] *Spectra and Bandwidth of Emissions*, ITU-R Recommendation SM.328-11 (05/06)

[15] *AM IBOC Ascertainment Project*, NAB Broadcast Engineering Conference, slides, CPB_IBOC_NAB_2005.pdf, duTreil, Lundin & Rackley/Hatfield & Dawson joint venture

[16] *Evaluation and Improvement of AM Antenna Characteristics for Optimal Digital Performance*, Ronald D. Rackley, pp. 206-214, 2004 NAB Broadcasting Engineering Conference Proceedings

[17] *Spectrum Analyzer Measurements and Noise*, Agilent Technologies, Inc., Application Note 1303, April 2, 2008

[18] *AM/FM IBOC Measurements with the Agilent N9340B Handheld Spectrum Analyzer*, Agilent Technologies, Inc., Application Note 5989-9969EN, November 14, 2008

[19] Pre-correction of Analog FM signals to correct for filterplexer distortions, Anders Mattsson, pp.397-401, 2006 NAB Broadcast Engineering Conference Proceedings

2.3 Symbols and abbreviations

In this Guideline the following abbreviations are used:

AM	Amplitude Modulation
ATU	Antenna Tuning Unit
DANL	Displayed Average Noise Level
EPM	Equipment Performance Measurements
ERP	Effective Radiated Power
FCC	Federal Communications Commission (U.S.)
FM	Frequency Modulation
IBOC	In-Band/On-Channel
IMD	Intermodulation distortion
MF	Medium Frequency
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation

QPSK	Quadrature Phase Shift Keying
RBW	Resolution Bandwidth
RF	Radio frequency
S/N	Signal-to-Noise ratio
VBW	Video Bandwidth
VHF	Very High Frequency

2.4 Definitions

In this Guideline the following definitions are used:

All digital waveform	A transmitted waveform for modes which do not include the analog-modulated signal. For FM IBOC, the all-digital waveform is composed entirely of digitally modulated subcarriers, while for AM IBOC, the all-digital waveform is composed of digitally modulated subcarriers and the unmodulated AM carrier.
Extended hybrid waveform	A transmitted waveform for modes composed of the analog FM signal plus digitally modulated primary main subcarriers and some or all primary extended subcarriers. This waveform will normally be used by broadcasters requiring additional digital capacity over that provided by the hybrid mode of operation (provides up to approximately 50 kbps additional capacity).
HD Radio™	Trademark (of iBiquity Digital Corporation) for the digital AM and digital FM transmission technology authorized by the FCC. Note that in the NRSC-5 Standard and its normative references, the use of the term "HD Radio" is interpreted as the generic term "IBOC" and should not be construed as a requirement to adhere to undisclosed private specifications that are required to license the HD Radio name from its owner.
Hybrid waveform	A transmitted waveform for modes composed of the analog -modulated signal, plus digitally modulated primary main subcarriers. This waveform will normally be used during an initial transitional phase preceding conversion to the all digital waveform.
Impedance bandwidth	The complex-impedance-versus-frequency characteristics of a system such as an AM transmission system. The complex impedance is commonly represented directly or indirectly in various ways, such as phase/amplitude, VSWR, and real/imaginary mathematical notation.
OFDM subcarrier	A narrowband PSK or QAM-modulated carrier within the allocated channel, which, taken together with all OFDM subcarriers, constitute the frequency domain representation of one OFDM symbol.
Pattern bandwidth	A description of the variations in RF frequency response versus azimuth of an AM antenna pattern.

Resolution bandwidth (RBW)	In a spectrum analyzer, the nominal bandwidth of the power detecting element of the device. The RBW is adjustable and often must be set at a specific value when trying to establish compliance with an RF mask.
RF mask	The graphical representation of the allowable RF signal power spectral density (relative to a specific bandwidth) versus frequency for an RF transmission. Typically, the power values are indicated relative to the power of an unmodulated signal at the center frequency of the signal.
Spectral regrowth	The phenomenon whereby the signal energy of a band-limited RF signal increases outside of the signal's necessary bandwidth, typically due to the existence of nonlinearities in the RF system.
Spectrum analyzer	An instrument used to characterize the amplitude (power) versus frequency characteristics of a signal.
Trap filter	An RF filter used to strongly attenuate the energy within a certain range of frequencies, typically characterized by a deep notch at the trapped frequencies and low insertion loss at the desired frequencies.

3 BACKGROUND

The purpose of an RF mask is twofold – interference control, and quality control. For controlling interference, the RF mask establishes the limits for the unwanted emissions (spurious and out of band emissions) and the limits for the desired emissions (within the necessary bandwidth).[1] Adherence to the mask improves the utilization of the spectrum and reduces interference potential among signals sharing the spectrum. By implementing an RF mask, particularly in the context of digital signals, intermodulation products, which are indicators of distortions of the transmitted signal, are kept within specified limits. The RF mask therefore also acts as a basic control on the quality of the transmitted signal.

IBOC transmission architectures have evolved to adapt to the engineering requirements of various types of broadcast facilities. Initially, FM IBOC facilities employed high-level combining to inject a digital signal into the transmission line of the analog signal destined for the antenna. Various FM IBOC implementations now combine the analog and digital signals at each of many points in the transmission chain, from the signal generation end (within the exciter) to the radiation end (at the antenna or in free space). Each architecture places constraints on the performance of the transmission equipment and on the methods of measuring the combined hybrid FM IBOC signal.

AM IBOC transmission architecture is not varied to the extent that it is with FM IBOC. However, AM IBOC systems have site-specific constraints largely dependent on the design and type of antenna system employed by the AM station. The nature of the relatively narrow bandwidth AM transmission system presents a challenge to the engineer attempting to measure conformance with the RF mask. What goes into the antenna system is not necessarily what comes out. Field measurement of AM signals is also potentially challenging because of the presence of potentially strong environmental noise and interference, including the energy of other stations within and near the necessary bandwidth of the AM IBOC signal.

Mask compliance is by definition analyzed by evaluating the power spectral density (PSD) of the signal and spurious emissions (PSD is described in the units of power per unit bandwidth, for example, dBm/kHz). The most common instrument for performing such analysis is the swept spectrum analyzer. The bandwidth is established by the resolution bandwidth filter, which approximates the ideal bandwidth employed to define the RF mask. Newer spectrum analyzers employ various digital techniques to improve the quality and accuracy of the measurement; in some instances an instrument that appears to be a swept spectrum analyzer is a fully digital RF analyzer that presents its results in a manner that looks like a swept analyzer. It is expected that as new products are developed for the industry innovative approaches to evaluating IBOC signals may evolve.

This Guideline is intended to support all hybrid and extended hybrid IBOC spectrum conformance work, but focuses primarily on the hybrid IBOC signal as used in the broadcast facility. While much of the discussion relates to where and how to make measurements at the transmitter site, this Guideline also provides developers of individual system components with a consistent and repeatable method of evaluating those components when they are deployed at the customer's broadcast facility. Such consistency of measurement among manufacturers fosters both competition and interoperability.

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[1] Reference [14] defines occupied bandwidth and necessary bandwidth of the desired emissions, as well as unwanted emissions, consisting of out-of-band emissions and spurious emissions.

4 HYBRID FM IBOC MASK COMPLIANCE MEASUREMENTS

4.1 Overview

For hybrid FM IBOC, the NRSC-5 Standard specifies, in Section 4.2.8, limits for noise and spuriously generated signals from all sources, including phase noise and intermodulation products. This specification is included here in Figure 1 and Table 1.

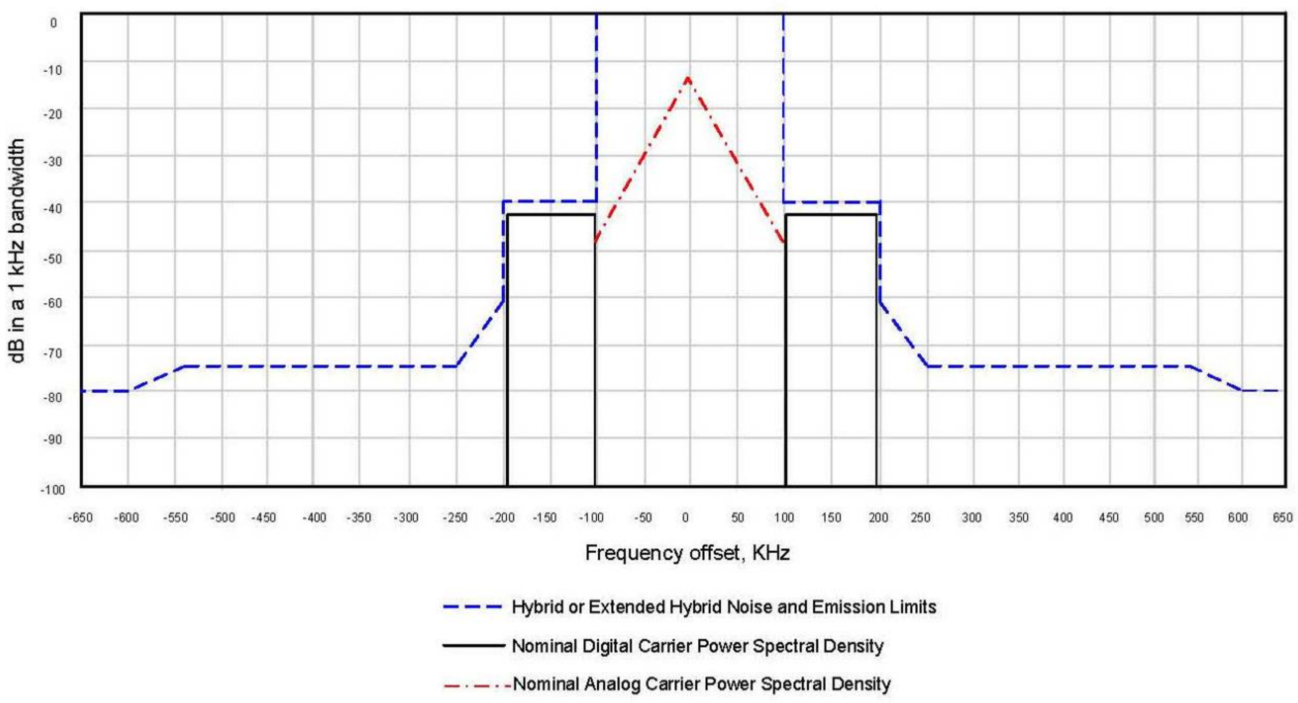

Figure 1. NRSC-5-B hybrid FM IBOC waveform noise and emission limits

Table 1. NRSC-5-B hybrid FM IBOC waveform noise and emission limits

Frequency offset relative to carrier, kHz	Level relative to unmodulated carrier, dBc/kHz
100 - 200	-40
200 - 250	-61.4 – (|frequency in kHz| - 200) x 0.260
250 - 540	-74.4
540 - 600	-74.4 – (|frequency in kHz| - 540) x 0.293
> 600	-80

4.2 Modulating signals and compliance measurements

The signal(s) used for modulating the analog portion of the HD Radio hybrid IBOC signal can introduce variance in RF mask compliance measurements. The shape of the PSD envelope of the analog portion of the hybrid signal is determined by the modulating signals applied to the analog carrier.[2] To determine if a transmitter is performing to manufacturer specifications for RF mask compliance, the recommended test configuration is the following:

- Terminate the transmitter output in a dummy load of adequate power rating;
- Operate the transmitter at the power level specified for the broadcast facility;
- Apply the recommended test signal:
    - Remove all modulation from the analog FM signal (no stereo pilot, no stereo subcarrier or other FM subcarriers)
    - Apply only a 1 kHz monaural tone at +/- 75 kHz total FM carrier deviation
- Simultaneously transmit the HD Radio sidebands.

The recommended test signal is repeatable, thereby eliminating variances in results due to the modulation. The recommended test signal has been found to generate fairly pronounced FM sideband components, which then contribute to the generation of more pronounced 3rd- and 5th-order intermodulation products if non-linearities are present in the transmitter. The recommended test signal has been found to be more “demanding” against the mask (by about 2 dB) than using “pink” noise or program audio.[3]

Transmitter setup with this test tone will result in more conservative operation under the mask when modulating with typical program material. This test signal is recommended for transmitter compliance testing into a dummy load. Regular program material may be used for final equipment performance measurements when the transmitter is connected to the antenna system.

The analog FM modulation frequency of 1 kHz is recommended so that the FM deviation of the analog carrier is not affected significantly by the presence or lack of audio pre-emphasis. Therefore, the 1kHz monaural tone can be input via either a balanced audio input or the wideband, composite, input of an FM exciter.

Operational mask measurements, with the transmitter connected to its transmission system, may be made with the station’s normal program modulation.

4.3 Operational facilities

There are two types of hybrid FM IBOC facilities of concern to the individual who must make measurements. The first is the “common-line” facility—the facility that combines the analog and digital components of the hybrid FM signal at some point before it reaches the antenna. The composite hybrid IBOC signal can be sampled from the common transmission line after all combining and filtering components in the system. The second is the “separate-line” facility where the composite hybrid signal is not available for sampling on any transmission line.

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[2] Note that the shape of the PSD envelope of HD Radio digital sidebands is, on the average, independent of the information being transmitted. This is because the modulation of the digital signals is maintained by processes that randomize the modulating information in a white noise-like fashion.

[3] Several modulation types were considered for RF mask compliance measurements, and the 1 kHz monaural tone was selected as the most effective. It is relatively unaffected by pre-emphasis and produces simple repetitive sidebands. In contrast, experiments have shown that it is not as effective to apply more complex modulation to the analog FM carrier. For instance, modulation with a 15 kHz tone at +/- 75 kHz deviation with L = -R (stereo mode), and unmodulated subcarriers at 67 and 92 kHz (both at 5% injection), results in substantial analog spectrum spreading, which contributes to less pronounced 3rd and 5th order RF intermodulation distortion (IMD) products.

Common-line facilities include those that use high power combining (Figure 2), split-level combining, low-level combining, or direct synthesis of the hybrid signal. Measurement of common-line facilities is readily done with a single transmission line tap.

Figure 2. High-power combiners such as the one shown here are used to combine the outputs of separate analog and digital transmitters and require a dummy load which will typically dissipate a significant amount of power. (Courtesy of Shively Labs)

Separate-line facilities never combine the digital and analog signals within the transmission plant. In each case of the separate-line facility, there are two transmission lines extending between the IBOC station's transmitters and antennas. Measurement of separate-line facilities requires careful calculation of the individual gains and losses on the digital and analog systems to establish a reference level between them.

Separate-line facilities include those that use separate antennas or dual-fed antennas. Separate antenna systems utilize two physically separated antennas, either on the same tower or on different towers within relatively close proximity. Interleaved antenna systems employ two antenna arrays whose bays are interleaved within the same aperture on the tower (Figure 3). Dual-fed antennas are antennas that have two inputs per bay, linked to the antenna elements by a four-port hybrid combiner.

Figure 3. Example of an interleaved antenna which is used to "space combine" the analog and digital portions of an FM IBOC signal. Note that every other bay is fed the analog signal directly by the high power transmission hard-line running vertically behind the bays. The alternate bays are fed the digital signal component by the black coaxial cables running horizontally from the tower to the array (denoted by yellow arrows). Close inspection of the antenna elements reveals that the alternating bays are circularly polarized in opposite directions. (Courtesy of Shively Labs)

4.3.1 Common-line facilities

4.3.1.1 Measurement location and sampling method

To obtain a sample of the hybrid FM IBOC signal at a common-line broadcast facility, identify the last component in the signal chain before the signal is sent to the antenna.

Figure 4 contains two examples of simple common-line FM systems. The stars mark the location at or beyond which the analog and digital signals are on a common transmission line. If there are filters or a master antenna combiner, obtain the RF sample after the last component. This ensures that the measurement will capture any bandpass characteristics affecting signal flatness, and any possible non-linear effects from other transmitters or arcing components in the transmission system.

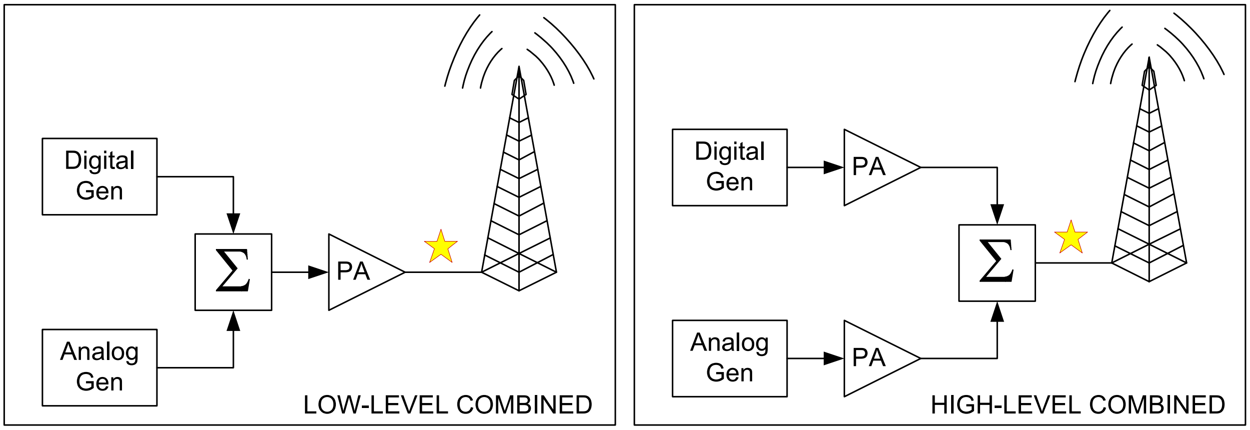

Figure 4. Two examples of simple common-line FM systems

To be certain that the common-line sample is representative of the radiated signal, two primary concerns should be addressed—antenna bandwidth and sample quality. First, while most FM antennas are sufficiently broadband to reliably radiate the hybrid IBOC signal, it is important to be certain that the system being tested has an antenna that meets these requirements. Normally, knowing the frequency for which the antenna was tuned, and the manufacturer's specifications for the antenna should be sufficient. In special cases such as those that involve a station at the edge of a master antenna's passband, or an antenna that may have been obtained inexpensively from a station on a different frequency, it is advisable to sweep the antenna to determine if there are any significant bandwidth anomalies that require attention.

The second concern, and the one more likely to be a source of difficulty in obtaining a representative sample of a hybrid FM IBOC signal, is the quality of the directional coupler employed to obtain a sample. First of all, a simple signal sampling loop may not be reliable because it is not directional. Unwanted energy feeding into the reverse path on the transmission line might affect the quality of the measurement from the loop. Also, when employing a directional coupler, the coupler should have a directivity of at least 30 dB, and potentially more in challenging environments with strong reverse-path signals.

The RF sample should be strong enough to maximize the signal-to-noise ratio (S/N) in the measuring instrument. At the same time, the level at which the RF sample arrives at the input to the measurement instrument's first mixer, converter or detector should not overload the instrument. This is discussed further in Section 6.1.1.

4.3.1.2 Instrument configuration

When a reliable signal is obtained from the sample port, it is time to establish a power reference, set up the instrument span and bandwidth, and configure the detector, sweep and averaging functions. For further information see Section 6.2 on measuring.

4.3.1.3 Spurious emissions

The intermodulation of the digital and analog components of the hybrid FM IBOC signal potentially produces spurious emissions at regular intervals (nominally 164 kHz on center) above and below carrier frequency (see Figure 5). Further intermodulation products may occur in the manner that traditional analog facilities sometimes experience at multi-transmitter sites. Just as the two analog signals of co-located stations may intermodulate and produce sum and difference products within and near the FM band, so, too, may the analog and digital components of a hybrid signal interact with the analog and digital components of co-located stations' signals. It is recommended that a third-order intermodulation study be prepared before evaluating a new or modified facility. This may help the evaluator to identify emissions observed during the test and to determine whether the station under test is the cause of the spurious emission.

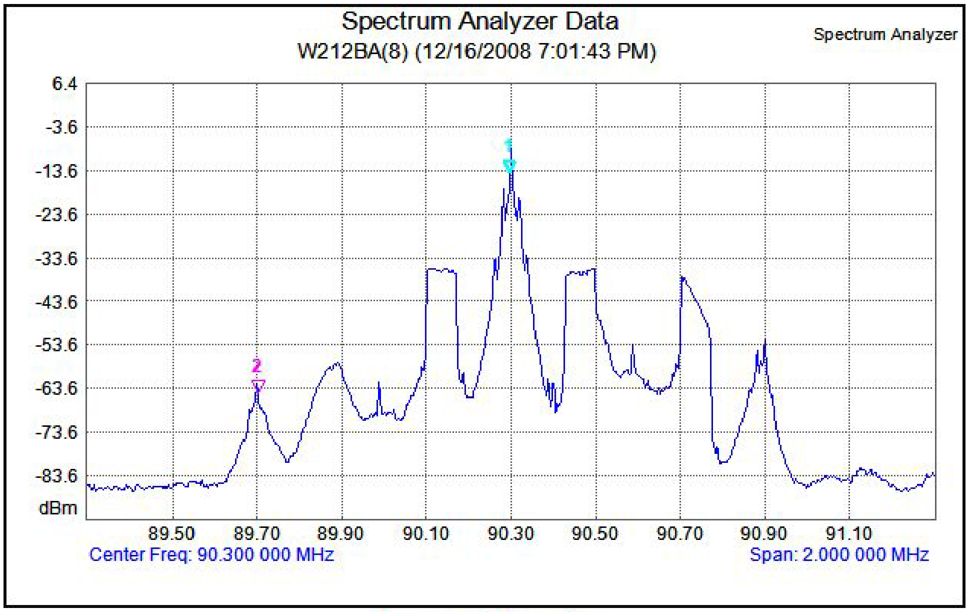

Figure 5. Example of spurious emissions sampled from the output of an FM IBOC transmitter. The spurious emissions in this image are generated by the transmitter and are predominantly the result of some unwanted signals overloading the transmitter's power amplifier. See Figure 7 for an example of IBOC spectral regrowth at 164 kHz intervals. (Courtesy of Broadcast Signal Lab)

While attention in this document is primarily focused on the desired emission and nearby out-of-band and spurious emissions, transmitter harmonics are another critical source of spurious emissions. The hybrid FM IBOC mask extends indefinitely outside the bounds of Figure 1, incorporating the station's harmonic frequencies. The sample point for the hybrid FM IBOC common-line signal should be after the harmonic filter has had an opportunity to attenuate harmonic emissions.

The directional coupler may be broadband enough for establishing levels of spurious emissions within and near the FM spectrum, depending on the passband of the directional coupler. However, additional care must be taken with harmonic measurements. The coupler response may understate harmonic power, thereby artificially lowering the apparent level of harmonic products. If the coupler's response to harmonics is known and a corresponding correction is made to the measured harmonic level, a reliable worst-case harmonic measurement is obtained from the transmission line. It is reasonable to assume that harmonics will be further attenuated by the antenna before being radiated.

When measuring harmonics, it is helpful to insert an FM band "trap filter" whose insertion loss and response at the harmonic frequencies is known. This reduces the power of the incoming fundamental frequency, reducing the possibility that the analyzer's internal harmonic distortion will be mistaken for a transmitted harmonic product.

Another valuable tip for working with harmonic and intermodulation products on an analyzer involves testing an apparent spurious emission for whether it is emitted by the system under test or internally generated by the measurement instrument. If the instrument is being forced into a non-linear range that causes internal spurious products, the addition of attenuation to the input of the instrument will change the spurious component by more than the value of the attenuator. For example, with the insertion of a 10 dB attenuator, all external signals entering the instrument will be attenuated by 10 dB. However, any internally generated spurious signals will diminish by more than 10 dB, because the internal process is not linear. This is a helpful test when confronted with a spur and uncertain about the performance of the instrument.

4.3.2 Separate-line facilities

4.3.2.1 Measurement location and sampling method

Obtaining a sample of the hybrid FM IBOC signal at a separate-line broadcast facility is more challenging that at a common-line facility. There is no place, except over the air, from which to sample the hybrid FM IBOC signal. Unfortunately, over-the-air measurements are subject to inconsistencies resulting from differing antenna patterns for the analog and digital signals and to multipath in the signal received by the test instrument.[4] In addition, over-the-air reception is subject to noise, interference and signals on channel adjacencies that could mask the presence of non-compliant emissions. Consequently, over-the-air measurements are not recommended for assessing hybrid IBOC FM signals for RF mask compliance.

For separate-line system mask compliance measurements, it is recommended that independent analog and digital signals samples be obtained and carefully compared to determine if mask compliance is achieved. Figure 6 contains two examples of simple separate-line systems. The stars mark the locations at or beyond which the independent analog and digital signals should be sampled. If there are filters or a master antenna combiner, obtain the RF sample after the last component. This ensures that the measurement will capture any bandpass characteristics affecting signal flatness, and any possible non-linear effects from other transmitters or arcing components in the transmission system.

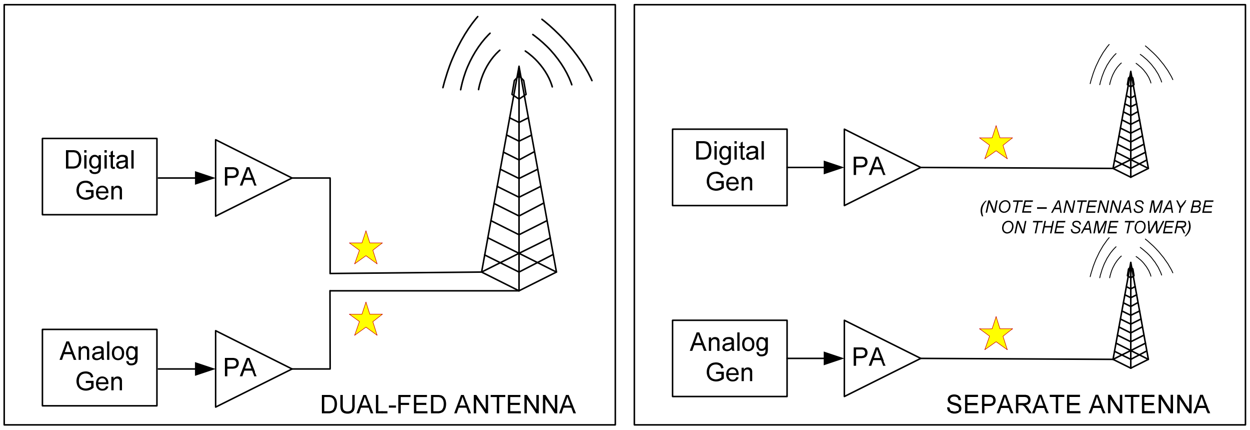

Figure 6. Two examples of simple separate-line FM systems

To be certain that the separate-line sample ports obtain samples that are representative of the radiated signal, two primary concerns should be addressed—antenna bandwidth and sample quality. First, while most FM antennas are sufficiently broadband to reliably radiate the hybrid IBOC signal, it is important to be certain that the system being tested has an antenna that meets these requirements. Normally, knowing the frequency for which the antenna was tuned, and the manufacturer's specifications for the antenna should be sufficient. In special cases that involve a station at the edge of a master antenna's passband, or an antenna that may have been obtained inexpensively from a station on a different

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[4] It is recommended practice to have the separate antenna systems for analog and digital signals operate with antenna vertical and horizontal patterns, antenna heights and antenna positions that are as similar as possible to minimize variations in the analog-to-digital power ratios in the field. See also §73.404 (d) of the FCC rules.

frequency, it is advisable to sweep the antenna to determine if there are any significant impedance bandwidth anomalies that require attention.

The second concern, and the one more likely to be a source of difficulty in obtaining a representative sample of a hybrid FM IBOC signal is the quality of the directional coupler employed to obtain a sample. First of all, a simple signal sampling loop may not be reliable because it is not directional. Unwanted energy feeding into the reverse path on the transmission line might affect the quality of the measurement from the loop. Also, when employing a directional coupler, the coupler should have a directivity of at least 30 dB, and potentially more in challenging environments with strong reverse-path signals.

This is a particular concern in separate-line systems because the isolation between the digital and analog transmission chains varies with the facility design. Low isolation figures can place greater demands on coupler directivity to avoid false indications of spurious emissions. In addition, the isolation in the separate-line systems may be insufficient for protecting the digital and the analog transmitters from ingesting too much energy from the other transmitter. This is especially the case with a digital transmitter that is confronted with an incoming (reverse path) analog signal with substantial power. Either transmitter, but especially the digital transmitter, may produce spurious emissions and digital signal distortions that could be masked by poor coupler directivity. Extra attention to isolation and coupler performance should be paid in the design of a separate-line hybrid FM IBOC system.

Since there is no place in the separate-line system where the ratio of the analog and digital signals is established empirically, special attention must be given to the system gains and losses on both the analog and digital systems. The ratio between the power of the digital and analog signals must be set by calculation and system design because they cannot be reliably observed in separate-line systems. The signal samples taken from directional couplers on the separate analog and digital transmission lines must be adjusted in power to obtain the correct relative power levels. The differences in line losses and antenna gains between the sample points and the respective antennas must be accounted for. In addition, the couplers' coupling ratios should be known as precisely as possible. With this information, one can make a reasonable comparison between the spectrum samples taken from the analog and digital lines and the RF mask, and in doing so, determine the analog to digital power ratio.

A tool to simplify the comparison of the analog and digital signals on separate-line systems has been studied. It is a test jig that combines the analog and digital signal samples from the separate lines to create a virtual common-line copy of the combined signals. It has been called the Combined Hybrid IBOC Measurement Package ("CHIMP"). In Annex 4, a white paper on the device is presented explaining how to make and use such a device and how the performance of the device was validated.

When performing separate-line sampling, the RF sample should be strong enough to maximize the S/N in the measuring instrument. At the same time, the level at which the RF sample arrives at the input to the measurement instrument's first mixer, converter or detector should not overload the instrument. This is discussed further in Section 6.1.1.

4.3.2.2 Instrument configuration

When reliable signals are obtained from the sample ports, it is time to establish a power reference, set up the instrument span and bandwidth, and configure the detector, sweep and averaging functions. For further information, see Section 6.2 on measuring.

4.3.2.3 Spurious emissions

The intermodulation of the digital and analog components of the hybrid FM IBOC signal potentially produces spurious emissions at regular intervals (nominally 164 kHz on center) above and below carrier frequency. Further intermodulation products may occur in the manner that traditional analog facilities sometimes experience at multi-transmitter sites. Just as the two analog signals of co-located stations may intermodulate and produce sum and difference products within and near the FM band, so, too, may the analog and digital components of a hybrid signal interact with the analog and digital components of co-located stations' signals. It is recommended that a third-order intermodulation study be prepared before evaluating a new or modified facility. This may help the evaluator to identify emissions observed during the test and to determine whether the station under test is the cause of the spurious emission.

While attention in this document is primarily focused on the desired emission and nearby out of band and spurious emissions, transmitter harmonics are another critical source of spurious emissions. The hybrid FM IBOC mask extends indefinitely outside the bounds of Figure 1, incorporating the station's harmonic frequencies. The sample points for the hybrid FM IBOC separate-line signals should be after the harmonic filters have had an opportunity to attenuate harmonic emissions.

The directional coupler used for signal sampling may be broadband enough for establishing levels of spurious emissions within and near the FM spectrum, depending on the passband of the directional coupler. However, additional care must be taken with harmonic measurements. The coupler response may understate harmonic power, thereby artificially lowering the apparent level of harmonic products. If the coupler's response to harmonics is known and a corresponding correction is made to the measured harmonic level, a reliable worst-case harmonic measurement is obtained from the transmission line. It is reasonable to assume that harmonics will be further attenuated by the antenna before being radiated.

When measuring harmonics, it is helpful to insert an FM band trap filter whose insertion loss and response at the harmonic frequencies is known. This reduces the power of the incoming fundamental frequency, reducing the possibility that the analyzer's internal harmonic distortion will be mistaken for a transmitted harmonic product.

Another valuable tip for studying harmonic and intermodulation products on an analyzer involves testing an apparent spurious emission for whether it is emitted by the system under test or internally generated by the measurement instrument. If the instrument is being forced into a non-linear range (due to signal overload) that causes internal spurious products, the addition of attenuation to the input of the instrument will change the spurious component by more than the value of the attenuator. For example, with the insertion of a 10 dB attenuator, all external signals entering the instrument will be attenuated by ten dB. However, any internally generated spurious signals will diminish by more than 10 dB, because the internal process is not linear. This is a helpful test when confronted with a spur and uncertain about the performance of the instrument.

Also, for separate-line systems, both the analog transmission line and the digital transmission line may show outgoing spurious energy on the same part of the spectrum. It is difficult to obtain a reliable sum of the power density spectrum of each to establish total power in the radiated spurious signal. The sum of co-frequency spurious emissions on the analog transmission line and the digital transmission line may to be non-compliant with the RF mask, while the individual images appear compliant. If so, further work is necessary.

For example, if the individual spurious emission on each transmission line were 1 dB below the mask, then the sum of these two co-frequency emissions would be 2 dB over the limit (the sum of two equal power signals represents a 3 dB increase in total power). To sum the co-frequency spurious emissions of both the analog and digital transmissions, the power values in decibels should be converted to linear values, summed, and reconverted to decibels. This would yield a composite value that is an approximation of the sum of the energy on the digital line and the analog line at that frequency. Alternatively, use the measurement combiner box (CHIMP) described in Annex 4 to sum the two sampled signals at the correct ratio to evaluate spurious emissions.

4.4 Troubleshooting (various out-of-spec conditions and possible remedies)

Distorted signals in FM systems are typically the result of amplification problems. In situations where there are filters and combiners, one must make certain that these devices are not excessively rolling off the frequency and phase response in the critical passband of the hybrid IBOC signal. Intermodulation products, generally caused by amplification problems, result in widened "shoulders" of the digital OFDM subcarrier sidebands and in "spectral regrowth" that appears as "beehive" bumps of energy out of the station's occupied bandwidth (see Figure 7). Intermodulation may also create the appearance of tilted OFDM sideband levels.

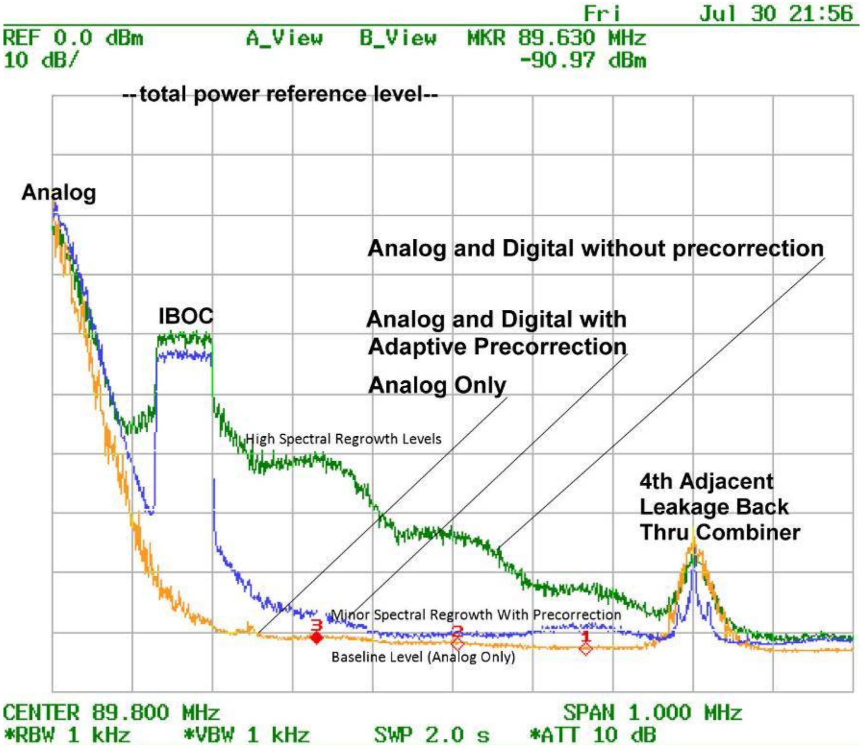

Figure 7. Some of the common distortions encountered in FM IBOC signals include "widened shoulders" of the digital OFDM subcarrier sidebands and "spectral regrowth" which appears beyond the main portion of the signal. (Courtesy of Broadcast Signal Lab)

4.4.1 Pre-correction and clipping discussion

It is important to maintain amplifier bias levels that conform to factory specifications. If the bias is too high, there is insufficient headroom for the power amplifier (PA) to handle the peaks. Also, if the exciter has fixed pre-correction (in which there is a factory or user setting that is set and stays put), it should be adjusted to anticipate the level of bias on the transmitter.[5] Poorly amplified IBOC signals will have considerable spectral regrowth and gain flatness may also appear to suffer.

4.4.2 Evaluating ingress of unwanted signals

Any system with two final PAs in parallel has the capacity to feed back energy from one into the other, potentially producing intermodulation products in the PAs. At multiple-station sites, signal energy from

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[5] "Pre-correction" refers to the technique by which the phase and/or magnitude response of the signal generating device is intentionally distorted to compensate for the overall phase and magnitude response of the system. See reference [19] for additional information.

other stations may also find its way into the output of the PA, complicating the situation with more intermodulation products. This unwanted energy imposed on a PA output can be one of the primary causes of non-complaint hybrid FM IBOC emissions.

On separate-line systems there is some degree of *isolation* between the two systems. The isolation can be measured using the reverse direction of the transmission line directional coupler. This is best done with one transmitter off-air while measuring the energy received by the transmission line of that off-air transmitter. The coupler has associated with it a coupling loss (for example, 50 dB below the power of the energy on the line in the direction being sampled) that can be used to help determine the isolation between the systems as shown in Equation 1:

Equation 1 (decibel addition & subtraction)

(Measured level of incoming signal)
+ (coupling loss)
– (Tx1 power out)
= (isolation between Tx1 and the sample point of the Tx2 system)

Turnaround loss of a transmitter indicates how much of the unwanted energy coming into its PA from the transmission line is turned around and sent back out to the antenna. Turnaround loss can be on the order of 6 dB, depending on the transmitter. Knowing the turnaround loss can help in estimating how much energy from one transmitter will be output by the other transmitter as shown in Equation 2:

Equation 2 (decibel addition & subtraction)

(Tx1 output power)
– (isolation)
– (turnaround loss of Tx2)
= (expected output power of Tx2's turning around Tx1 energy)

In other words, (isolation) – (turnaround loss) indicates how many dB below the Tx1 transmitted signal will be the distorted copy of the transmitted signal emitted by the Tx2 PA. To relate these to effective radiated power (ERP), one must account for line losses and antenna gains.

On systems with common-line configurations, turnaround loss is of most concern when high-level and split-level combining are used. Low-level combining does not present the same design challenges as combining the outputs of high power amplifiers. Direct synthesis begins with a combined hybrid signal from the digital-to-analog converter and has no active components that are separately handling analog and digital waveforms.

High-level and split-level combining can be evaluated with directional couplers on the outputs of the transmitters, before the combining network. High-level combining can be evaluated in the same manner as described above for separate-line evaluation, that is, by shutting off one transmitter while evaluating the isolation from the other transmitter. Since split-level combining requires the presence of some analog energy on both transmitters to make the hybrid combiner function as planned, measurements made by turning off one transmitter to measure the isolation to the other transmitter may be unreliable.

Care must be taken to ensure that any measurement in one direction on a directional coupler is not compromised by signal traveling in the other direction on the transmission line. Directional couplers have a "directivity" figure that indicates how much the forward signal crosstalks into the reverse port and vice versa. Measurements can be limited by the directivity of a coupler, especially when the coupler has a strong signal passing through it in the direction opposite to the direction being sampled.

4.4.3 Error rate testing

Digital waveforms can be analyzed for their deviation from an ideal waveform carrying the same information. In the analog domain there are various methods of representing how well each data symbol reaches the target value of phase and magnitude for that symbol. Timing, amplitude, and phase distortions contribute to errors in the digital radio signal. NRSC-5-B contains a specification for the performance of the error vector magnitude ("EVM") of the IBOC digital waveforms.[6] Error vector magnitude describes the amplitude of the average error of the data symbols from their ideal value. When the EVM at a given location is increased, there will be more errors in reception.

Another analog measure of digital signal quality is the modulation error ratio ("MER"). This is related to EVM in that it also measures the magnitude of the errors in the data symbols, but with respect to a slightly different reference value.

In the digital domain, it is also customary to detect the digital data stream and evaluate the accuracy of the resulting bitstream compared to the original. This is the bit error ratio ("BER"), reporting the number of bit errors in ratio with the total number of bits evaluated. The raw BER takes the demodulated data stream as-is to generate the ratio. There is also a post-error-correction BER that applies the digital system's built-in error correction features and identifies only those bit errors that remain after error correction.

Error correction techniques tends to exhibit a cliff effect, in that the output remains relatively error free until the algorithm is overwhelmed with errors and the output error rate then rises steeply. For this reason, a post-error-correction BER will tend to mask subtle impairments in the signal under test. Engineers often evoke the image of "using up the error correction" when transmitting a distorted digital signal, because there is less error correction "headroom" for the impairments caused by the propagation and reception of the digital signal when the transmitted signal has significant impairments already.

Presently, there is only the EVM specification in NRSC-5-B that could be employed for measuring the quality of the transmitted signal. It is anticipated that tools for making such measurements will become available for characterizing the quality of the digital signal. The NRSC may consider recommending and/or adopting other specifications (such as MER or BER) as the IBOC industry continues to mature and new measurement tools and techniques become available.

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[6] See NRSC-5-B Reference Document 6, FM Transmission System Specifications and Chapter 9 of reference [5].

5 HYBRID AM IBOC MASK COMPLIANCE MEASUREMENTS

5.1 Overview

For hybrid AM IBOC, the NRSC-5 Standard specifies, in Section 4.1.8, limits for noise and spuriously generated signals from all sources, including phase noise and intermodulation products. This specification is included here for 5 kHz mode (Figure 8 and Table 2) and 8 kHz mode (Figure 9 and Table 3).

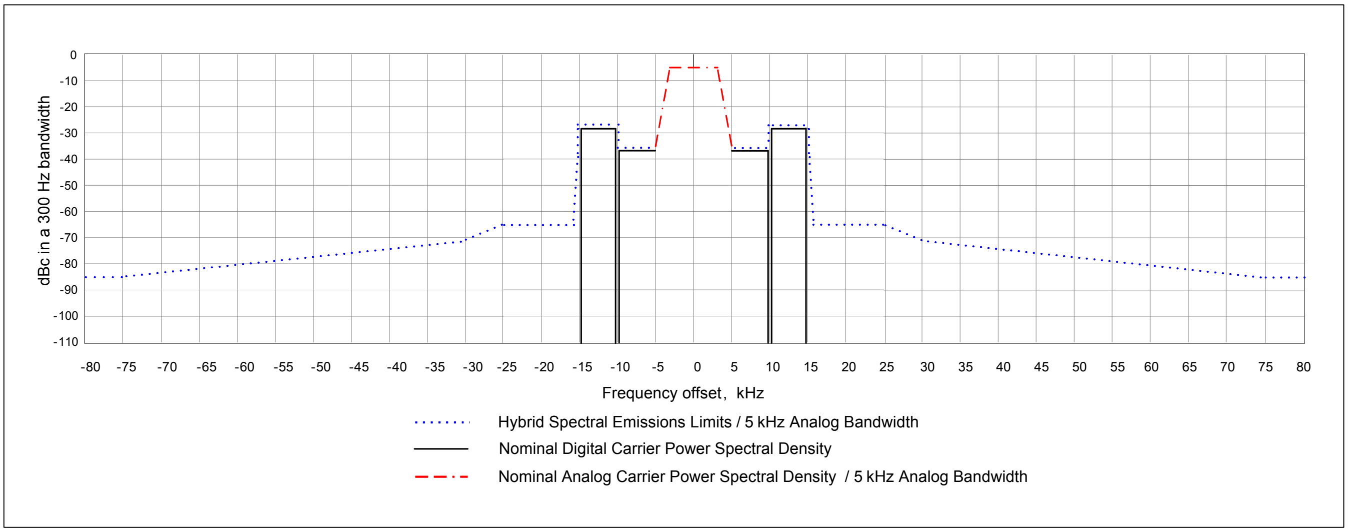

Figure 8. NRSC-5-B hybrid AM IBOC waveform spectral emissions limits for 5 kHz mode analog bandwidth

Table 2. NRSC-5-B hybrid AM IBOC waveform spectral emissions limits for 5 kHz mode analog bandwidth

Frequency offset relative to carrier, kHz	Level relative to unmodulated carrier, dBc per 300 Hz
5 - 10	-34.3
10 - 15	-26.8
15 - 15.2	-28
15.2 - 15.8	-39 – (|frequency in kHz| - 15.2) x 43.3
15.8 - 25	-65
25 - 30.5	-65 – (|frequency in kHz| - 25) x 1.273
30.5 - 75	-72 – (|frequency in kHz| -30.5) x 0.292
> 75	-85

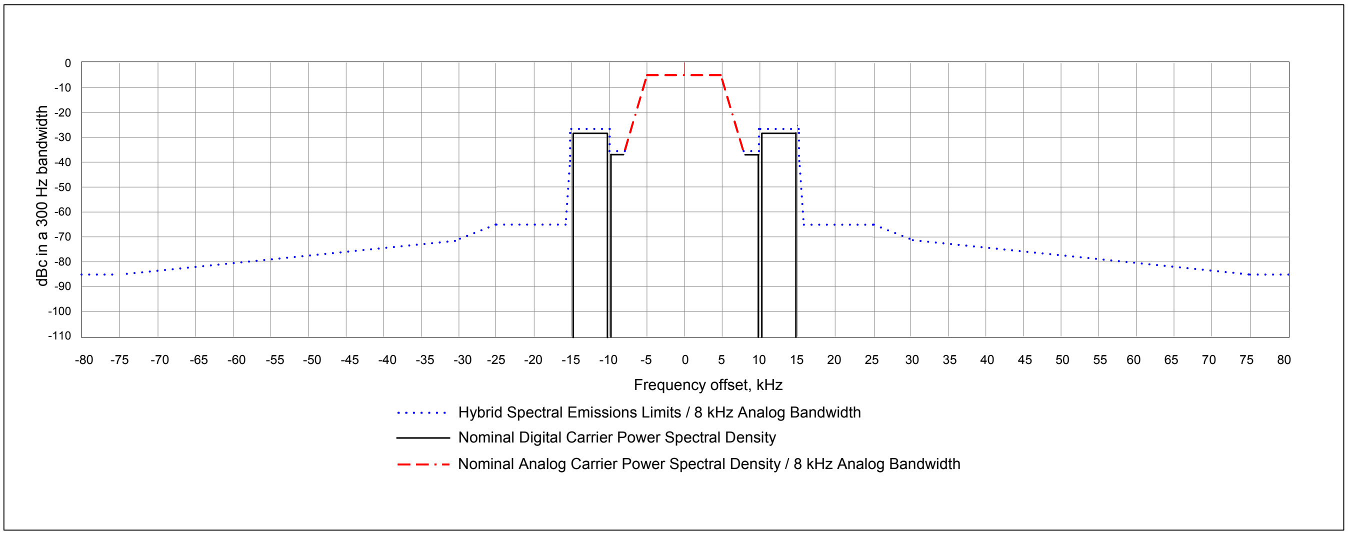

Figure 9. NRSC-5-B hybrid AM IBOC waveform spectral emissions limits for 8 kHz mode analog bandwidth

Table 3. NRSC-5-B hybrid AM IBOC waveform spectral emissions limits for 8 kHz mode analog bandwidth

Frequency offset relative to carrier, kHz	Level relative to unmodulated carrier, dBc per 300 Hz
8 - 10	-34.3
10 - 15	-26.8
15 - 15.2	-28
15.2 - 15.8	-39 – (|frequency in kHz| - 15.2) x 43.3
15.8 - 25	-65
25 - 30.5	-65 – (|frequency in kHz| - 25) x 1.273
30.5 - 75	-72 – (|frequency in kHz| -30.5) x 0.292
> 75	-85

In addition to performing a measurement of the hybrid AM IBOC signal against the hybrid IBOC mask, the NRSC-5-B standard also calls for a measurement of the analog-only AM signal against the FCC mask described in 47 CFR §73.44.

5.2 Operational facilities

Field measurement of hybrid AM IBOC signals is necessary because the antenna system has such a strong influence on the quality of the radiated signal that sampling the transmitter output may not be representative of the signal characteristics. However, there are specific transmission sampling techniques that make it possible to rely on transmitter output measurements to verify RF mask compliance. Such verification is conditional and subject to field verification in the event that an interference issue or mask compliance concern is raised. The specific sampling techniques are explained below.

The antenna system will for the most part not generate intermodulation-based spurious emissions on its own. Only in the event of a significant nonlinearity in the antenna system (such as an arcing condition in the mechanics of the system) is it possible that the antenna system will generate new intermodulation products that might exacerbate spectral regrowth or create other spurious emissions. In addition to transmitter amplification non-linearities, impedance mismatches between the transmitter and antenna system can contribute to the creation of intermodulation products (spectral regrowth) in the transmitter final amplifier. Furthermore, the impedance bandwidth and pattern bandwidth characteristics of the antenna system can attenuate or enhance spectral regrowth sidebands with respect to the center frequency and antenna azimuth.

Issues relating to the pattern bandwidth of the antenna system can affect the digital-to-analog power ratios and can roll off certain portions of the hybrid signal at certain azimuths from the directional array. This Guideline does not address pattern bandwidth issues, other than to recommend taking off-air measurements within the main lobe of the pattern.

5.2.1 Directional and non-directional antenna systems

There is little difference between measuring directional and non-directional antenna systems. Directional systems have a main lobe within which the hybrid IBOC signal should be at optimum level and performance. Mask compliance in directional arrays, when measured in the field, is determined by measurements made on a main lobe, within the ±3 dB geographic arc around the peak of the main lobe. Non-directional systems may be measured in any direction from the antenna site where local noise and interference are minimal and the desired signal strength is sufficient to provide good dynamic range in the measurement.

5.2.2 Measurement locations and sampling methods

5.2.2.1 Field measurement

The reference location for measuring hybrid AM IBOC mask compliance in the field is the same as the NRSC-2 measurement location. A location approximately 1 km from the antenna site is suggested. The objective is to site the measuring equipment optimally:

a) in the far field of the antenna system;
b) as close as possible to the antenna to maximize signal level and to minimize measurement noise and ambient noise; and
c) as remotely as possible from sources of interference, noise, and re-radiation that may confound the results.

Measurements of stations with directional antenna patterns should be made at a point within ±3 dB of the peak of the main lobe. For NRSC-5 mask compliance measurements, the reference level is the actual analog signal power level observed at the time the measurement is taken.

A good quality shielded loop antenna is commonly employed to peak the signal and minimize electrical noise pickup such as that shown in Figure 10.

Figure 10. AM field measurements are best made with a good quality shielded loop antenna. (Courtesy of Chris Scott & Associates)

5.2.2.2 True power measurement at transmitter

Since sometimes it can be difficult to obtain reliable measurements of AM IBOC mask compliance in the field, a measurement from the AM transmission line using the proper technique can serve as an acceptable secondary measurement method. However, if there is reason to believe that the transmission line measurement is incorrect, a field measurement may be necessary. Transmission line samples may be taken between the transmitter and the next component in the system, typically the common point or antenna tuning unit (ATU) as the case may be.

The signal sampling technique used is critical to the accuracy of the measurement. Because the impedance of a typical AM antenna system varies across the bandwidth of the hybrid IBOC signal, a simple voltage or current sample will not suffice due to the uncertainty introduced by the voltage and current standing wave in the presence of a load mismatch. Using a directional coupler eliminates the error due to the standing wave and will provide accurate forward and reflected power samples. As a result, the use of a directional coupler is recommended. Note that many installations and transmitters are not equipped with directional couplers so this would need to be added in order to obtain accurate power samples.

The sampling technique must obtain an accurate measurement of the real, delivered power accepted by the antenna system across the frequency range of interest. Mathematically, this requires sampling the voltage (magnitude and phase) and current (magnitude and phase) and forming the scalar product of the two (“dot product”), taking into account forward and reflected power and vector summing the samples (prior to making the dot product calculation).

A practical method of obtaining a measurement of real, delivered power is to subtract the reflected PSD from the forward PSD at each frequency of interest. Since the objective is to obtain the radiated PSD by frequency, the power sampling method must be unaffected by the variation in impedance across the bandwidth of interest.

Note that if the reflected PSD is not subtracted from the forward PSD the resulting measurement will be higher that the real PSD and therefore will be a more conservative measurement of out-of-band emissions. In general, this error is relatively small and may be acceptable without correction. For example, if the reflected PSD measured is 10 dB below the forward PSD (return loss = 10 dB, VSWR = 1.9:1) the forward PSD measurement is 0.5 dB higher than the real PSD. If the reflected PSD measured is 3 dB below the forward PSD (return loss = 3 dB, VSWR = 5.8) then the forward PSD is 1.8 dB higher than the real PSD.

5.2.2.3 Impact of pattern bandwidth

Transmission line measurements do not account for the pattern bandwidth, which is a description of the variations in frequency response versus azimuth of the AM antenna pattern. Typically, the performance of the hybrid IBOC signal in the main lobe will be similar to the results of the transmitter output true power sample method described above. On other radials, and especially at nulls, the center frequency may be more depressed than other frequencies in the hybrid IBOC channel, or outside the channel. The result can appear as distortion of the PSD of the hybrid IBOC signal compared to the main lobe and transmission line measurements and the appearance of non-compliant OFDM subcarrier levels and spectral regrowth levels with respect to the mask. For this reason, only field measurements in the main lobe are applicable to compliance measurement.

5.2.2.4 Directional coupler measurements not for compliance assessment

For diagnostic purposes only, it may be helpful to take a directional coupler sample from the output of the transmitter or a sample from the common point bridge. If the sample is taken from the bridge, set the reactance (X) and resistance (R) dials detuned as far as possible so as to not place a null in or tip the response of the spectrum of interest as observed at the common point's bridge detector's output.

The station should first be set up and confirmed to be mask-compliant in the field. Then, a transmitter output or common point sample spectrum plot can be taken as a baseline reference value and saved for future reference. For diagnostic purposes, a quick check of the transmission system performance can be made by comparing a new transmission line or common point sample with the original on file. These samples are not intended to verify mask compliance, but to show whether there has been a change in the characteristics of the signal at this point in the transmission system since it was first set up.

5.2.3 Analog signal and digital sidebands

Establishing the carrier reference level is a vital step in measuring mask compliance. FCC rules contained in 47 CFR §73.44 require the use of the *non-directional* power received at a measurement site to be the reference carrier level for analog AM mask measurements. This has always been problematic because it imposes a carrier-to-interference ratio penalty on the main lobe of a directional array that is equal to the gain of the array in the main lobe.

For the purposes of hybrid AM IBOC mask compliance, it is the actual *directional* carrier level received at the measurement point in the main lobe that establishes the carrier reference. This is because the well-transmitted hybrid AM IBOC signal has digital carriers that are quite close to the mask levels without exceeding them. Using a non-directional carrier reference on the main lobe of the pattern would cause the digital subcarriers to fall below their specified target levels for optimum performance.

Spectral regrowth can be caused by non-linearities in the amplification system, including poorly aligned magnitude and phase inputs, bias errors, and reflections caused by mismatches between the transmitter and the antenna system (see Figure 11). Spectral regrowth occurs out of the main passband of the antenna system and is likely to be attenuated by the antenna system to some degree. It is therefore often beneficial to also examine the transmitter output as a diagnostic tool for evaluating how the transmitter is behaving as part of the larger complex system.

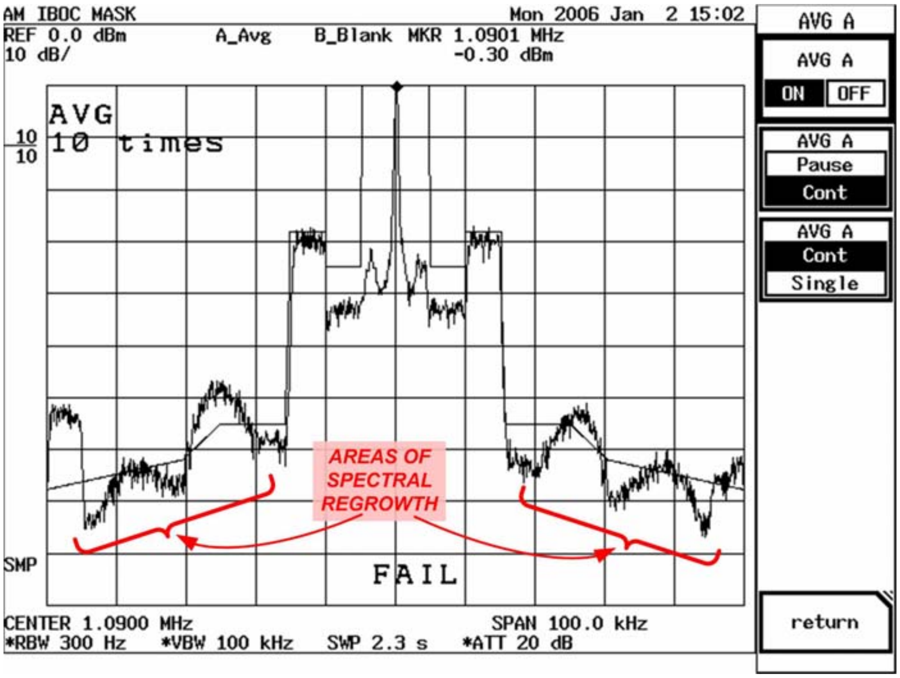

Figure 11. AM IBOC spectral regrowth can be caused by non-linearities in the amplification system, bias errors, and reflections caused by mismatches between the transmitter and antenna systems. (Courtesy of Broadcast Signal Lab)

Spectral regrowth, however, can appear to be amplified by the antenna system on some radials from directional arrays. This occurs when there are variations in the pattern bandwidth on certain radials where the main carrier is attenuated more than the sidebands. Compliance, however, is not dependent on the off-axis performance of the hybrid AM signal. Field evaluation for compliance only occurs in the main lobe of the directional array. The directional station may need to address an off-axis emission in response to specifically identified interference issues, on a case-by-case basis.

See Section 6.3 on measuring for further information.

5.2.4 Spurious emissions

AM stations are capable of receiving the emissions of other AM stations and then transmitting the resulting intermodulation products. These spurious emissions can be evaluated anywhere around the non-directional station and on the main lobe of the directional array, provided the receiving antenna has a known frequency response at the frequency of the spurious emission.

Spurious emissions are best observed using “peak-hold” measurements such as those specified in 47 CFR §73.44.

5.2.5 AM IBOC mask compliance measurement procedures

To harmonize the use of the 47 CFR §73.44 analog peak mask ("legacy mask") and the NRSC-5 hybrid IBOC PSD masks (shown in Figure 8 and Figure 9), the following protocol is recommended. If this protocol conflicts with present or future FCC rules or enforcement policy, the broadcast engineer should conform to the legal obligations of the station. Note that when performing AM IBOC mask compliance measurements, normal program modulation should be used.

NRSC-5-B reference document 1082s, Section 4.4, calls for a three-step procedure for verifying that an hybrid AM IBOC transmission is in compliance with the relevant RF masks. These measurements should be repeated (as appropriate) for each mode of station operation.

The first step is to verify that the analog-only portion of the transmission is in compliance with 47 CFR §73.44 (the legacy mask). This measurement is done using "peak-hold" measurement techniques.

The second step (also specified in Section 4.4 of NRSC-5-B reference document 1082s) calls for a hybrid IBOC mask measurement to be performed on the analog-only signal, with the mask extended at -65 dBc/300 Hz from 5 to 20 kHz offset for ±5 kHz analog operation (and to -65 dBc/300 Hz from 8 to 20 kHz offset for ±8 kHz operation). This measurement is done using "averaging" measurement techniques. Note that if peak-hold measurements were used in this step, the relative amplitude of the digital sidebands with respect to the mask (and also to the analog host) would be different than for averaging measurements.

The third step involves verifying that the full AM hybrid signal (with both digital and analog components) is compliant with the relevant hybrid AM IBOC mask (either Figure 8 or Figure 9). This third step is called out in Section 4.5 of NRSC-5-B reference document 1082s.

To perform the these measurements, the following sequence is recommended:

1) **Legacy analog mask measurement** – perform a peak-hold measurement of the analog-only signal. The hybrid IBOC transmitter should be operating with the digital sidebands temporarily disabled. This measurement follows the procedure specified under 47 CFR §73.44. Employ the §73.44 mask, activate peak hold on the measuring instrument at 300 Hz resolution bandwidth, collect data under normal program modulation for 10 minutes.

   Performing this measurement ensures that any impulsive noise generated by the analog transmission is captured and compared to against the FCC legacy analog mask.

2) **Analog-sideband-to-digital overlap measurement** – with the analog-only signal still transmitting, perform a power averaging measurement with the hybrid IBOC mask measurement method. The hybrid IBOC transmitter should be operating with the digital sidebands temporarily disabled. Verify that the analog-only signal of a ±5 kHz-limited analog transmission does not exceed -65 dBc/300 Hz PSD (power averaging) between the 5 kHz offset and the 20 kHz offset above and below the carrier frequency. If the analog signal is set to the ±8 kHz bandwidth, verify that the analog-only signal does not exceed -65 dBc/300 Hz PSD (power averaging) between the 8 kHz offset and the 20 kHz offset above and below the carrier frequency.

   Performing this measurement ensures that the analog transmission meets the NRSC-5-B specification for self-interference from the analog to the digital components of the hybrid IBOC signal within the ±20 kHz bandwidth of the station.

3) **Full Hybrid IBOC Measurement** – Restore the full hybrid IBOC signal (analog and digital components) and perform a hybrid IBOC mask measurement. This is the measurement that is specified in Reference [1], Section 4.5 and explained further above. Use the 300 Hz resolution bandwidth and power averaging function. Follow the procedure described above for the 100 sweep/30 second time period measurement.

This measurement ensures that the hybrid IBOC signal and its spectral regrowth components remain within the NRSC-5-B mask.

5.2.5.1 Additional legacy mask on full hybrid signal measurement

The NRSC-5-B standard specifies the three measurements above. This additional measurement is helpful as a diagnostic tool, for instance, if impulsive noise is observed while the hybrid AM IBOC signal is transmitting.

To do this additional measurement, perform a §73.44 peak-hold mask measurement on the full hybrid AM IBOC signal (with both digital and analog components present). This measurement is useful because of the complex interactions which occur between the analog and digital components of the hybrid AM IBOC signal – see Annex 6 for additional information.

5.2.5.2 Harmonics

When measuring harmonics with a spectrum analyzer (instead of a narrowly tuned field intensity meter), it is helpful to insert an AM band trap filter whose insertion loss and response at the harmonic frequencies is known. This reduces the power of the incoming fundamental frequency, reducing the possibility that the analyzer's internal harmonic distortion will be mistaken for a transmitted harmonic product. A calibrated antenna (or calibrated sampling port on a transmission line, if applicable) is necessary for accurate measurements of harmonics. The NRSC-5 spectral mask applies to harmonic measurements of hybrid IBOC AM signals.

5.2.5.3 Testing for instrument-induced harmonic and spurious content

Another valuable tip for studying harmonic and intermodulation products on an analyzer involves testing an apparent spurious emission for whether it is emitted by the system under test or internally generated by the measurement instrument. If the instrument is being forced into a non-linear range (due to analyzer input overload) that causes internal spurious products, the addition of attenuation to the input of the instrument will change the spurious component by more than the value of the attenuator.

For example, with the insertion of a 10 dB attenuator, all external signals entering the instrument will be attenuated by 10 dB. However, any internally generated spurious signals will diminish by more than 10 dB, because the internal process is not linear. This is a helpful test when confronted with a spur and the performance of the instrument is uncertain.

5.3 Troubleshooting (various out-of-spec conditions and possible remedies)

Before the hybrid AM IBOC transmission is evaluated for RF mask compliance, a number of initial design and installation steps are required to optimize system performance, including:

- The antenna system should be tuned, and if necessary, redesigned to be tuned, to provide the impedance bandwidth and Hermitian symmetry desired of a well-running AM IBOC system. See Annex 5;
- The transmitter impedance matching filter (output network) rotates the passband on the Smith Chart and must be accounted for when designing the antenna system characteristics and taking impedance measurements;

- Transmitters having phase and magnitude inputs should be adjusted per manufacturer specifications to obtain the ideal phase/magnitude input alignment;

- The output of the hybrid AM IBOC transmitter should be as clean as possible to ensure that the signal gets off to the best start possible.

5.3.1 Error rate testing

Digital waveforms can be analyzed for their deviation from an ideal waveform carrying the same information. In the analog domain there are various methods of representing how well each data symbol reaches the target value of phase and magnitude for that symbol. Timing, amplitude, and phase distortions contribute to errors in the digital radio signal. NRSC-5-B contains a specification for the performance of the error vector magnitude ("EVM") of the IBOC digital waveforms.[7] Error vector magnitude describes the amplitude of the average error of the data symbols from their ideal value. When the EVM at a given location is increased, there will be more errors in reception.

Another analog measure of digital signal quality is the modulation error ratio ("MER"). This is related to EVM in that it also measures the magnitude of the errors in the data symbols, but with respect to a slightly different reference value.

In the digital domain, it is also customary to detect the digital data stream and evaluate the accuracy of the resulting bitstream compared to the original. This is the bit error ratio ("BER"), reporting the number of bit errors in ratio with the total number of bits evaluated. The raw BER takes the demodulated data stream as-is to generate the ratio. There is also a post-error-correction BER that applies the digital system's built-in error correction features and identifies only those bit errors that remain after error correction.

Error correction techniques tends to exhibit a cliff effect, in that the output remains relatively error free until the algorithm is overwhelmed with errors and the output error rate then rises steeply. For this reason, a post-error-correction BER will tend to mask subtle impairments in the signal under test. Engineers often evoke the image of "using up the error correction" when transmitting a distorted digital signal, because there is less error correction headroom for the impairments caused by the propagation and reception of the digital signal when the transmitted signal has significant impairments already.

Presently, there is only the EVM specification in NRSC-5-B that could be employed for measuring the quality of the transmitted signal. It is anticipated that tools for making such measurements will become available for characterizing the quality of the digital signal. The NRSC may consider recommending and/or adopting other specifications (such as MER or BER) as the IBOC industry continues to mature and new measurement tools and techniques become available.

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[7] See NRSC-5-B Reference Document 6, FM Transmission System Specifications and Chapter 9 of reference [5].

6 MEASUREMENT METHODOLOGY

6.1 Spectrum analyzers

6.1.1 Input levels

Total broadband RF power into the instrument's mixer, detector, or converter should be well below its 1 dB compression level to allow for peaks on desired and undesired signals to be handled without distortion and without resulting in internal generation of false signals. When evaluating the actual input level to the instrument, not only must the total RF power of all signals present on the sample line be considered, but also the internal attenuator setting should be accounted for.

Spectrum analyzers have internal input attenuators that can be manually or automatically engaged. The instrument operator should keep in mind that analyzers correct displayed readings to compensate for the value of the internal attenuation. This means that the operator must calculate the total power reaching the input mixer to determine how much mixer headroom there is.

If, for example, the total power delivered to the instrument's input connector were 0 dBm, and the internal attenuator is set to 10 dB, then the input power to the first stage is -10 dBm. This is true even though the analyzer reports the level as 0 dBm. In this example, after determining the total input power to the first active stage of the analyzer is -10 dBm, the headroom can be calculated. If the 1 dB compression level of the analyzer were +7 dBm, the addition of the 10 dB of internal attenuation gives the instrument a comfortable 17 dB headroom between the total input power (average) to the first stage and the 1 dB compression level.

The operator should keep in mind that IBOC digital signals, in the absence of the analog signal, may have peak to average ratios in the vicinity of 4-6 dB, which should be considered in ensuring that there is sufficient headroom for an accurate measurement. Likewise, undesired signals also arriving at the input to the instrument may contribute average and peak power levels that must be accounted for in setting the input level.

6.1.2 Dynamic range

The noise floor of instrumentation being used for mask compliance measurement should be at least 10 dB below the mask minimum for best results. For example, the most restrictive level of the hybrid AM IBOC mask is -85 dBc. The instrument noise floor should be therefore -95 dBc or lower. This prevents instrument noise from summing with the measured value to create a false appearance of non-compliance.

Spectrum analyzer performance is characterized by various measures. The first measures to examine are the displayed average noise level (DANL) and the 1 dB compression level. Be aware that the DANL varies with frequency, requiring careful attention to the DANL frequency and its resolution bandwidth settings. When scaled to the desired resolution bandwidth for the measurement, the factory DANL should be low enough to offer the desired dynamic range. Note that contemporary spectrum analyzers typically have published specifications for noise levels and other characteristics beginning at 10 MHz, and above. Instrument noise levels may be higher at frequencies lower than 10 MHz, requiring verification by demonstration that the instrument's performance in the AM band meets the dynamic range requirements.

To determine the noise floor requirements for a mask compliance measurement device, use Equation 3:

Equation 3 (decibel addition & subtraction)

(1 dB compression level)
– (margin to handle peaks without compression)
– (difference between total input power and input power of signal under test)
– (greatest mask clearance from signal under test reference level to lowest value of mask)
– (noise floor margin to resolve space below mask)
= (required noise floor)

Careful reading of the instrument specifications, while accounting for resolution bandwidths used in the specifications, may reveal whether the instrument has the minimum necessary dynamic range. As Equation 3 shows, if the input level of the signal under test is below the 1 dB compression level by a very large margin, then the instrument noise floor must be correspondingly lower. This may occur if the instrument is receiving other strong signals in addition to the signal under test or if the signal under test is weak and cannot be brought up to the desired input level.

Considering that, for AM measurements, it is sometimes difficult to get a strong signal at a field test point, the actual input level of the signal to the analyzer may need to be substantially lower in level than is optimal. Similarly, for FM measurements there may be multiple strong signals on, for instance, a master transmission line, so the input level of the signal under test may need to be lower than in the example above, to account for the total power of all signals and the peak power of those signals appearing at the instrument's input. In all these cases, additional instrument dynamic range or low noise input amplification will be necessary to accommodate weaker desired signal levels.

To illustrate Equation 3, assume a particular instrument has a +7 dBm 1 dB compression level. We want to allow plenty of room for the peaks of multiple incoming signals to sum without affecting the measurement, so in this example a headroom margin of 15 dB is selected to be sure that the simultaneous occurrence of peaks of several incoming signals have some headroom. Assume that the desired signal is one of 6 equal power signals on a master antenna system, which means the average power of the desired signal is 8 dB down from the total input power (= 10* log [1/6]). The hybrid FM IBOC mask's lowest limit line is -80 dBc. As noted above, this Guideline recommends at least 10 dB between the mask minimum and the instrument noise floor. Using Equation 3:

+7 dBm	(1 dB compression level)
– 15 dB	(margin to handle peaks without compression, selected on case-by-case basis)
– 8 dB	(difference between total input power and input power of signal under test)
– 80 dB	(greatest mask clearance from signal under test reference level to lowest value of mask)
– 10 dB-kHz	(noise floor margin at desired resolution bandwidth to resolve space below mask)
= -106 dBm/kHz	(required noise floor)

So for this example, -106 dBm/kHz will be the maximum acceptable displayed average noise level. Note that the required instrument noise floor calculated in the example may not be directly comparable to the manufacturer's specification. For instance, a specification might indicate that an instrument has a -130 dBm/Hz noise floor at the desired frequency. Increasing the bandwidth from 1 Hz PSD to 1 kHz increases the noise by a factor of 1000, or 30 dB. Consequently, the instrument has a displayed average noise level of -130 dBm/kHz + 30 dB = -100 dBm/kHz.

Other instrument performance measures include intermodulation specifications in several forms. It is not the role of this document to explain these specifications in detail, only to make the reader aware of them. An instrument may have a satisfactory noise floor, but the intermodulation specifications must be good enough that its ability to identify real spurious emissions of a hybrid IBOC signal is not compromised by internally generated products. There is no better way to evaluate an instrument than to try it out on signals whose performance is already known.

6.1.3 Resolution bandwidth (RBW) and noise bandwidth

Resolution bandwidth (RBW) is one of the most important parameters to be selected in setting up the spectrum analyzer. RBW can be thought of as the amount of bandwidth that is analyzed for each measurement point on a spectrum analyzer trace. RBW is typically established using selectable bandwidth filters within the analyzer. Most analyzers can select the RBW automatically, usually as a function of the frequency span being analyzed, and in addition provide for manual selection of RBW.

When making IBOC mask compliance measurements, it is customary to use a 1 kHz RBW for FM IBOC and a 300 Hz RBW for AM IBOC since these are the bandwidths used in expressing the masks (Figure 1, Figure 8, and Figure 9). However, there may be a reason for employing a different RBW, as explained in more detail in Annex 1.

RBW filters have associated with them a particular *noise bandwidth*. Noise bandwidth refers to the effective bandwidth of a filter (or other device) when measuring noise or noise-like signals. Noise bandwidth affects measurements of the OFDM digital sidebands because OFDM signals are noise-like. For example, two filters may have the same 3 dB bandwidth but have different width on the skirts. The filter with wider skirts will collect more “noise” power from the digital signals being measured than will the filter with narrower skirts, and hence will have a larger noise bandwidth.

The power of a digital signal reported by the spectrum analyzer for a given RBW is actually overstated by some error value. The amount of overstatement is a function of the noise bandwidth of the type of filter used in the analyzer. To obtain a correct power reading from a spectrum analyzer display, the effect of the noise bandwidth on the measurement of a digital signal should be subtracted:

- *4-pole synch tuned analog filters*: subtract 0.5 dB from readings
- *Gaussian analog filters*: subtract 0.24 dB from readings
- *Gaussian filters implemented digitally*: inconsequential (0.01 to 0.02 dB)

Some (newer) instruments can account for the RBW filter noise bandwidth when measuring digital signals. The operator should be as familiar as possible with the features of the instrument.

6.1.4 Detectors

The noise-like nature of modulated OFDM waveforms affects certain analyzers. Older units that use a “sample” detector and simply average the trace data on the log display implicitly understate the power by approximately 2.5 dB. Newer units may appear to average the trace but could be averaging the power data from which the trace is derived, without the 2.5 dB error. Newer units may also have “average power” detectors, (also called “RMS” detectors) that accurately measure digital signal power. Some instruments have an “average” detector that is not an average power detector, but a max/min averaging method applied to the maximum and minimum value in each measurement bin. Consult the instrument manual or the manufacturer to learn about the detectors available.

Alternatively, rather than adjusting the reading for this 2.5 dB error, the mask can be adjusted when creating a reference level (or limit line) on an instrument to take this into account. The correction may be subtracted from the published mask or added to the reading. For instance, an old analyzer with 4-pole filter, sample detector, log trace averaging would have 2.5 – 0.5 = 2.0 dB added to the reading (by lowering the reference level 2.0 dB below the carrier level), or the same amount would be subtracted from the mask overlaid on the instrument as a limit line.

It is recommended that a spectrum analyzer with an average power or RMS detector be obtained to eliminate the need for the 2.5 dB correction. For improved accuracy, the RBW filter noise bandwidth still should be accommodated, unless the unit employs digital filtering.

Traditional analog measurements under the FCC §73.44 legacy mask are performed with the peak detector, 300 Hz RBW, and an accumulation of 10 minutes of sweeping on a display set to maximum hold.

6.1.5 Limit lines

Limit lines are a convenient feature for evaluating the compliance of a measured signal with its mask. Contemporary spectrum analyzers have the ability to draw limit lines that represent spectral masks (see limit lines, in green, shown in Figure 12). Consult with the instrument's manual for instructions on how to program, store, recall, and set a reference level for limit lines. Some instruments will also indicate on the display whether the measured spectrum passes or fails the limit line test.

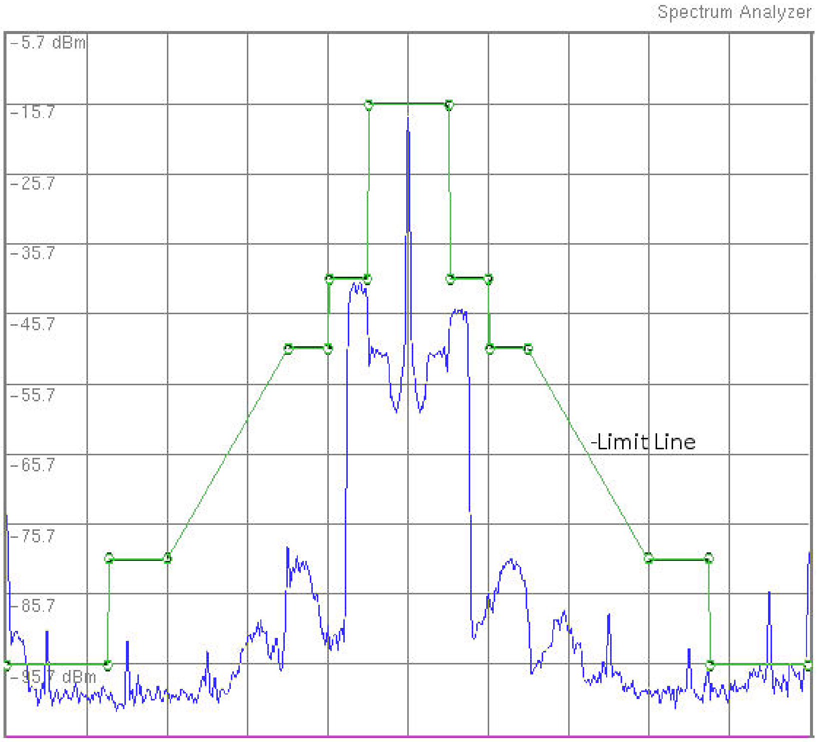

Figure 12. Limit lines are a powerful tool and can greatly simplify mask compliance measurements. (Courtesy Burt Weiner Associates and Broadcast Signal Lab)

6.2 FM setup – spectrum analyzers

6.2.1 Setting frequency span

The frequency span for Hybrid FM IBOC measurements is most conveniently set to about 500-600 kHz to provide sufficient detail of the hybrid IBOC signal while maintaining a full view of the hybrid IBOC signal. The center frequency may then be offset to each side of the display to look at upper and lower sideband spectral regrowth and spurs with similar detail. Alternatively, to view the hybrid FM IBOC signal and at least the first digital spectral regrowth energy at ±492 kHz offsets, use 1.2-2 MHz span with the carrier at center frequency.

6.2.2 Resolution bandwidth (RBW)

The default RBW for FM IBOC measurements is 1 kHz. The characteristics of the RBW filter may slightly affect the results (see Section 6.1.3 above). Assuming the spectrum analyzer employs the traditional four-pole synchronous filters or filters with narrower skirts, the hybrid FM IBOC mask provides plenty of room between the response of common 1 kHz RBW filter skirts and the mask slope at 200-250 kHz. However, if a station routinely has difficulty making the mask on this slope with a traditional analyzer with 4-pole analog filters, the station may do one of two things to improve its chances:

- First, stations may employ a narrower RBW, such as 100 Hz, 10 Hz, or even 1 Hz. The resulting measurements, at 100 HZ RBW, will be 100/1000 lower in level (i.e., 10 dB), so either the mask must be lowered 10 dB (as a limit line on the instrument) or the measurement must be compensated by increasing the result by 10 dB. Either way, the use of the narrower resolution bandwidth may improve the response on the slopes and determine that the mask has indeed been satisfied;

- The second alternative to addressing a mask-slope compliance problem is to employ a spectrum analyzer with narrower shape-factor filters. Gaussian filters (digital or analog) operated at the 1 kHz RBW may be sufficient to confirm the signal is within the mask. The goal of making such changes to the measurements is to minimize the error contributed by the instrument in order to verify compliance of the signal with the mask.

Alternatively, there may not be a mask-slope issue. If so, it may produce results more quickly to use a wider RBW as long as it confirms compliance and does not create the appearance of failure. With a 4-pole analog filter, the widest practicable RBW for FM mask measurements is 3 kHz. Any wider bandwidth competes with the slope of the mask. With a digital Gaussian filter, a bandwidth slightly wider than 6 kHz may be employed. The mask must be adjusted to compensate for the change in bandwidth and any change in the filter noise bandwidth should be accommodated. For example, using a Gaussian 6 kHz RBW filter, the mask should be adjusted up by 10 x Log(6 kHz/1 kHz) = 7.78 dB

In Annex 1, an explanation of how the power spectral density measurements of IBOC signals can be normalized to an equivalent power spectral density per Hz is given. Even if the spectrum analyzer or other instrument cannot measure to 1 Hz resolution, such normalization permits use of virtually any RBW, as long as the appropriate adjustments to the mask are made.

6.2.3 Video bandwidth

The video filter smoothes out the sweep as it displays, potentially robbing the operator of a view of the fine structure of the occupied spectrum. It is suggested that to observe gain flatness and repeatable spiky behavior, the video filter is best turned off or set to a value that is at least ten times the resolution bandwidth (*e.g.*, 10 kHz for a 1 kHz RBW setting).

6.2.4 Detector

Use “average power” or “RMS” detector if available. If not, use a “sample” detector with trace averaging. Do not use an “average” or “mean” detector that averages the max and min value in each bin. Peak detection should not be used for IBOC mask compliance measurements.

6.2.5 Reference level

Ideally, an unmodulated analog FM carrier is used to establish the reference level for determining mask compliance. Set the peak of the unmodulated carrier to the top of the spectrum analyzer display; having done so, the top of the display becomes the 0 dBc reference level. To conveniently identify the peak and set it to the reference level, use the marker function on the spectrum analyzer, if available; use the "find peak" function, then select "set marker to reference level".

If modulation cannot be removed, use a wide RBW (300 kHz for FM IBOC is a good choice) and determine the power level at the center frequency when modulation is present (Figure 13). Conducting this measurement over numerous sweeps is not necessary, but will help remove what little noise there is in the reference level. Then, set the power level measured at the center frequency (using the wide RBW) to the reference level at top of display; the top of the display now corresponds to 0 dBc. There is a minor error due to the presence of the IBOC signals within the passband of the 300 kHz RBW at center frequency, but it is inconsequential (0.04 dB at most).

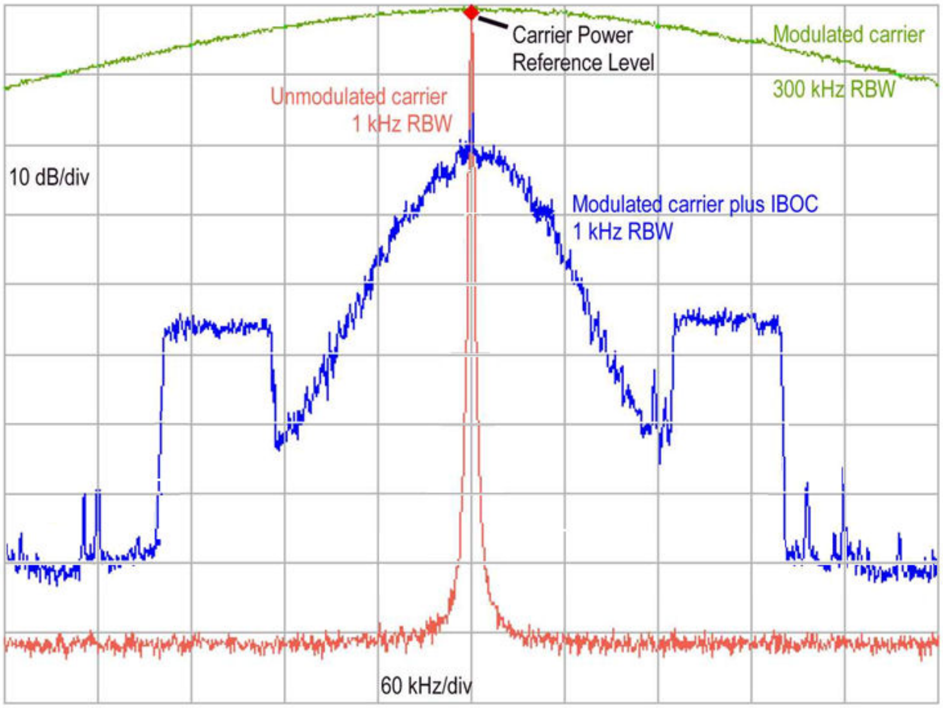

Figure 13. When a modulated signal is used to set the 0 dBc reference level, use a wide resolution bandwidth setting (300 kHz is used here), then use the power level at the center frequency to establish the reference level. (Courtesy of Broadcast Signal Lab)

Note that three different sweeps are shown in Figure 13:

- the unmodulated carrier (brown sweep);
- the modulated carrier plus IBOC with a 1 kHz RBW (blue sweep);
- the modulated carrier plus IBOC with a 300 kHz RBW (green sweep).

6.2.6 Sweep rate and number of sweeps

The sweep rate will be optimized if the instrument is left on “Auto” sweep as the RBW is selected. When setting manually, the rule of thumb is to take one-half of the square of the RBW as the target sweep rate. At 1 kHz RBW, the optimum sweep rate is approximately 500 kHz per second (instruments may calculate faster rates based on their preset parameters; these may be relied upon). Sweeping too quickly will cause the dynamics of the signal on each sweep to be missed. Sweeping too slowly has no measurement consequence. With old instruments and sample detection, more sweeps yield a better average, and sweeping more slowly than necessary merely wastes time. However, newer instruments with average power or RMS detectors are efficient at any rate slower than the maximum Auto rate. They may be swept very slowly, taking a long-term trace, or an average of a few traces; or they may be set to sweep more quickly to average many quick traces.

The goal is to take a measurement of the signal over a period that is long enough to minimize the variance between successive measurements. The benefit of averaging multiple sweeps is that the operator can watch the average accumulate and then determine visually when the result has stabilized. The NRSC-5 transmission system specification calls for 100 sweeps. The sweep rate formula (or Auto Sweep mode) determines the minimum time required to obtain 100 sweeps. Set up in this fashion, measurements will certainly have a low variance. This is an effective way to document results. For faster analysis and examination work, the operator can limit the number of sweeps to that which is necessary to observe and make adjustments. Also, for quicker results, a narrower sweep bandwidth (“span” on a spectrum analyzer) reduces the time necessary to complete a sweep.

The NRSC-5 transmission system specifications also call for a minimum of 30 seconds of data accumulation on the spectrum analyzer. By using the highest reliable sweep rate and the narrowest span necessary for a period of time that includes at least 100 sweeps, the elapsed time may be more or less than 30 seconds, depending on the span utilized. To comply literally with the specification, there should be at least 100 sweeps and a collection time of at least 30 seconds.

As a practical matter, experience has shown that 100 sweeps taken at the maximum applicable sweep rate is sufficient for obtaining a low-variance measurement, regardless of the time required to complete the sweeps. Thus, for analyzers set to sweep at the auto rate – at most span settings – the number of sweeps tends to be the controlling factor above the exact duration of the measurement.

Alternatively, for instruments that can perform accurate averaging without requiring multiple sweeps (*e.g.*, average power/RMS detection and FFT-based analyzers), it is acceptable to determine by experimentation how much time is required to perform a measurement that minimizes the variance between measurements. With these instruments, the number of sweeps may be one or very few, in which case the duration of the measurement is the controlling factor over the number of sweeps.

6.2.7 Interpreting results

There will always be some degree of variation between two measurements, whether due to different instruments, different operators, or measurements taken at a different time. The greatest source of spectrum analyzer uncertainty in IBOC RF mask measurements is in the detection and averaging functions. These are covered in detail in this Guideline.

The amplitude uncertainties of spectrum analyzers are of less concern. Specifications for spectrum analyzers provide several figures to describe various amplitude uncertainties present in the apparatus, including among others, frequency response, band switching, IF gain, RBW, and attenuator switching uncertainties. Fortunately, most of these uncertainties are minimized or eliminated because IBOC mask measurements are relative measurements. The reference analog carrier power is very close in frequency to the IBOC spectrum under test and there is no need to switch the instrument input characteristics once the input level and bandwidth has been set.

One exception is when the analog FM signal power is obtained on a modulated signal with a 300 kHz or wider RBW, followed by RBW switching to 1 kHz for the mask measurement. In this case, the RBW switching uncertainty applies. Typically, it is reasonable to expect that the amplitude uncertainty of a well-performing analyzer performing IBOC RF mask measurements will be well within ±2 dB, with the results being very likely to be within ±1 dB.

Another cause of uncertainty in measurements against the FM IBOC RF mask is the quality of the source. The response of the directional coupler used to obtain the FM IBOC signal sample may affect the results, particularly of out-of-band spurious emissions. In the case of separate-line systems, the estimates of gains and losses on the digital and the analog transmission paths are likely to have discrepancies on the order of 1-2 dB that confound accurate evaluation of the analog-to-digital power ratio. Finally, the presence of unwanted energy from other sources can corrupt the results. Such energy could be introduced through reverse path crosstalk in the coupler, test cable pickup of radiated or conducted energy, and potential instrument-generated intermodulation and harmonic products.

A well-conducted and reported FM IBOC mask compliance measurement will include documentation of the results, the methodology, and the uncertainties. The results should include both numeric and graphic presentations of measurement data. The methodology should include procedure and equipment descriptions as well as set-up diagrams. The uncertainties should include discussion of the potential sources of measurement error and any special challenges faced in taking the measurement.

6.3 AM setup – spectrum analyzers

6.3.1 Setting frequency span

The frequency span for hybrid AM IBOC measurements is most conveniently set to about 40-50 kHz to provide sufficient detail of the hybrid IBOC signal. The center frequency may then be offset to look at upper and lower sideband spectral regrowth and spurs with similar detail. Alternatively, to view the hybrid AM IBOC signal and at least the first spectral regrowth energy at ±25 kHz offsets, use 60-100 kHz span with the carrier at center frequency.

6.3.2 Resolution bandwidth (RBW)

The default RBW for AM IBOC measurements is 300 Hz. The characteristics of the filter may affect the results (see Section 6.1.3 above. Typically, spectrum analyzers employ four-pole synchronous filters or filters with tighter skirts. The hybrid AM IBOC mask is quite close to the slope of the 4-pole synchronously tuned RBW filter in the 15.0 to 15.2 kHz region. It may seem contradictory that this slope is 200 Hz wide and is being measured by a 300 Hz RBW filter. However, because this is a power spectral density measurement, and there are likely to be several data points (measurement bins) from 15.0 to 15.2 kHz, the analyzer is integrating the power in a 300 Hz bandwidth at each data point. The mask slope was selected to insure that under ideal conditions the hybrid IBOC signal would register as compliant with the mask with a 300 Hz RBW. However, if a station routinely has difficulty making the mask on this slope with a traditional analyzer with 4-pole analog filters, the station may do one of two things to improve its chances.

- First, stations may employ a narrower RBW, such as 100 Hz, 10 Hz or even 1 Hz. The resulting measurements, at 100 Hz RBW, will be 100/300 lower in level (4.8 dB), so either the mask must be lowered 4.8 dB (as a limit line on the instrument) or the measurement must be compensated by increasing the result by 4.8 dB. Either way, the use of the narrower resolution bandwidth may improve the response on the slopes and determine that the mask has indeed been satisfied;

- The second alternative to addressing a mask-slope compliance problem is to employ a spectrum analyzer with narrower shape-factor filters. Gaussian filters (digital or analog) operated at the 300 Hz RBW may be sufficient to confirm the signal is within the mask. The goal of making such changes to the measurements is to minimize the error contributed by the instrument in order to verify compliance of the signal with the mask.

In Annex 1, an explanation of how the power spectral density measurements of IBOC signals can be normalized to an equivalent power spectral density per Hz is given. Even if the spectrum analyzer or other instrument cannot measure to 1 Hz resolution, such normalization permits use of virtually any RBW, as long as the appropriate adjustments to the mask are made.

6.3.3 Video bandwidth

The video filter smoothes out the sweep as it displays, potentially robbing the operator of a view of the fine structure of the occupied spectrum. It is suggested that to observe gain flatness and "spiky" behavior, the video filter is best turned off or set to a value that is at least ten times the resolution bandwidth (*e.g.*, 3 KHz for 300 Hz RBW setting).

6.3.4 Detector

Use "average power" or "RMS" detector if available. If not, use a "sample" detector with trace averaging. Do not use an "average" or "mean" detector that averages the max and min value in each bin. Peak detection should not be used for IBOC mask compliance measurements.

For traditional NRSC-2 measurements of analog-only AM signals to determine compliance with 47 CFR §73.44, use the peak detector and the peak hold functions of the analyzer.

6.3.5 Reference level

Ideally, an unmodulated analog AM carrier is used to establish the reference level for determining mask compliance. Set the peak of the unmodulated carrier to the top of the spectrum analyzer display; having done so, the top of the display becomes the 0 dBc reference. To conveniently identify the peak and set it to the reference level, use the marker function on the spectrum analyzer, if available; use the "find peak" function, then select "set marker to reference level".

If modulation cannot be removed, use a narrow RBW (300 Hz or less for AM IBOC is a good choice) and perform an average power measurement of the modulated carrier over numerous sweeps (average until subsequent averages do not change the level at center frequency significantly). When enough averages have been taken, determine the power level at center frequency using the zero span mode of the analyzer. Then, set the power level measured at the center frequency level to the reference level at top of display; again, the top of the display now corresponds to 0 dBc (see Figure 14). There may be a minor error due to the asymmetrical modulation (-99, +125%), but it is inconsequential, especially at a narrow RBW.

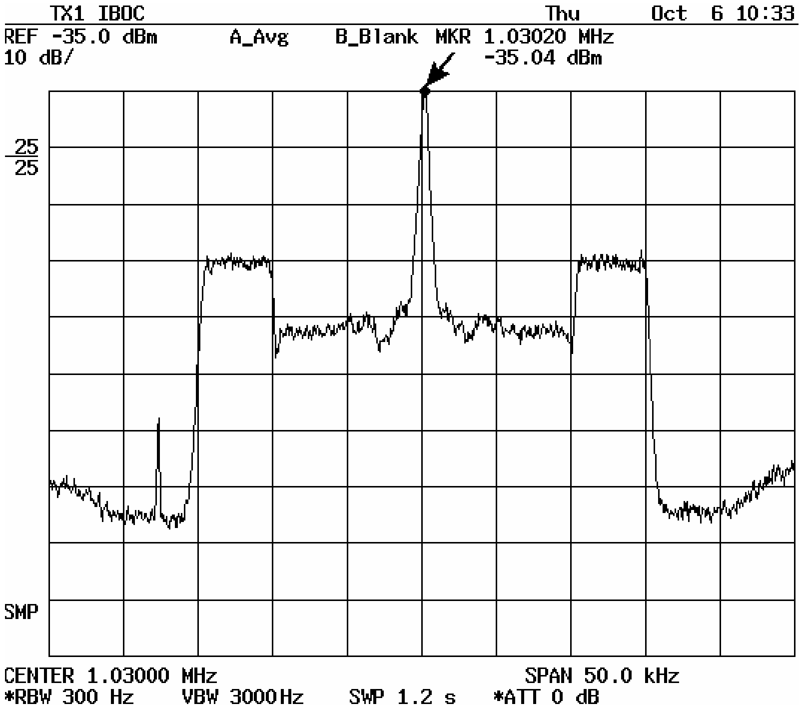

Figure 14. When a modulated AM signal is used to set the 0 dBc reference level, average the analyzer display over many traces, then use the power level at the center frequency to establish the reference level. (Courtesy of Broadcast Signal Lab)

6.3.6 Sweep rate and number of sweeps

The sweep rate will be optimized if the instrument is left on “Auto” sweep as the RBW is selected. When setting manually, the rule of thumb is to take one-half of the square of the RBW as the target sweep rate. At 300 Hz RBW, the optimum sweep rate is approximately 45 kHz per second (instruments may calculate faster rates based on the set parameters; these may be relied upon). Sweeping too quickly will cause the dynamics of the signal on each sweep to be missed. Sweeping too slowly has no measurement consequence. With old instruments and sample detection, more sweeps yield a better average, and sweeping slowly merely wastes time. However, newer instruments with average power or RMS detectors are efficient at any rate slower than the maximum Auto rate. They may be swept very slowly, taking a long-term trace or an average of a few traces; or they may be set to sweep more quickly to average many quick traces.

The goal is to take a measurement of the signal over a period that is long enough to minimize the variance between successive measurements. The benefit of averaging multiple sweeps is that the operator can watch the average accumulate and then determine visually when the result has stabilized. The NRSC-5 transmission system specification calls for 100 sweeps. The sweep rate formula (or Auto Sweep mode) determines the minimum time required to obtain 100 sweeps. Set up in this fashion, measurements will certainly have a low variance. This is an effective way to document results. For faster analysis and examination work, the operator can limit the number of sweeps to that which is necessary to observe and make adjustments. Also, for quicker results, a narrower sweep bandwidth (“span” on a spectrum analyzer) reduces the time necessary to complete a sweep.

The NRSC-5 transmission system specifications also call for a minimum of 30 seconds of data accumulation on the spectrum analyzer. By using the highest reliable sweep rate and the narrowest span necessary for a period of time that includes at least 100 sweeps, the elapsed time may be more or less than 30 seconds, depending on the span utilized. To comply literally with the specification, there should be at least 100 sweeps and a collection time of at least 30 seconds.

As a practical matter, experience has shown that 100 sweeps taken at the maximum applicable sweep rate is sufficient for obtaining a low-variance measurement, regardless of the time required to complete the sweeps. Thus, the number of sweeps implicitly takes precedence over the exact duration of the measurement.

Alternatively, for instruments that can perform accurate averaging without requiring multiple sweeps (e.g. average power/RMS detection and FFT-based analyzers), it is acceptable to determine by experimentation how much time is required to perform a measurement that minimizes the variance between measurements. With these instruments, the duration of the measurement implicitly takes precedence over the number of sweeps.

6.3.7 Interpreting results

There will always be some degree of variation between two measurements, whether due to different instruments, different operators, or measurements taken at a different time. The greatest source of spectrum analyzer uncertainty in IBOC RF mask measurements is in the detection and averaging functions. These are covered in detail in this Guideline.

The amplitude uncertainties of spectrum analyzers are of less concern. Specifications for spectrum analyzers provide several figures to describe various amplitude uncertainties present in the apparatus, including among others, frequency response, band switching, IF gain, RBW, and attenuator switching uncertainties. Fortunately, most of these uncertainties are minimized or eliminated because IBOC mask measurements are relative measurements. The reference analog carrier power is very close in frequency to the IBOC spectrum under test and there is no need to switch the instrument input characteristics once the input level and bandwidth has been set. Typically, it is reasonable to expect that the amplitude uncertainty of a well-performing analyzer performing IBOC RF mask measurements will be well within ±2 dB, with the results being very likely to be within ±1 dB.

Another cause of uncertainty in measurements against the AM IBOC RF mask is the quality of the source. In the field, the presence of energy generated by other sources may corrupt or mask the emissions of interest to the tester. Careful selection of a measurement site (or sites, if necessary) will minimize the potential interference. A directional antenna can be employed to isolate unwanted emissions in the spectrum or at least identify the direction from which they are coming

In cases where transmitter output measurements are being used to verify RF mask compliance, the response of the voltage and current vector sampling apparatus on the transmission line must be reliable or it may affect the results. Directional couplers and RF sampling loops may unreliably sample the spectrum in an AM transmission system and should only be used to benchmark performance for diagnostic purposes and future reference rather than for mask compliance purposes.

A well-conducted and reported AM IBOC mask compliance measurement will include documentation of the results, the methodology, and the uncertainties. The results should include both numeric and graphic presentations of measurement data. The methodology should include procedure and equipment descriptions as well as set-up diagrams. The uncertainties should include discussion of the potential sources of measurement error and any special challenges faced in taking the measurement.

7 FURTHER DEVELOPMENTS

It is anticipated that instrument manufacturers may develop innovative methods for evaluating signals and achieving compliance. They might not be in the form of traditional spectrum analyzers. Annex 1 of this document provides some insight into the malleability of the measurement technique to accommodate new methods while still maintaining compliance with the fundamental mask.

For Hybrid FM IBOC transmissions, higher digital power levels with respect to the analog host will likely complicate some of the issues discussed in this Guideline. The combined hybrid IBOC signal on a common transmission line will have a higher peak-to-average ratio than the original -20 dBc digital signal power, affecting transmitter linearity as well as measurement instrument linearity. With higher digital power levels comes greater potential for the digital output to crosstalk into the analog power amplifier (for separate amplification systems) and for spectral regrowth caused by amplifier non-linearities (in common amplification systems). The directivity of directional couplers employed to sample common line and separate line hybrid IBOC transmissions may need to be increased to provide greater front-to-back isolation for accurate measurements of PSD.

For hybrid AM IBOC transmissions manufacturers are already providing vector analysis of outgoing signal power with some transmitter products. With increasing market penetration and increasing industry experience with these devices, more precise and more useful measurements of AM signals will be available to more hybrid AM IBOC facilities.

ANNEX 1 – Discussion of a Tractable Approach to Defining and Measuring IBOC Signals Against RF Masks

A Tractable Approach to Defining and Measuring IBOC Signals against the RF Masks

By David Maxson, Broadcast Signal Lab, LLP, Medfield, MA, with significant conceptual and editorial contributions by Joe Gorin, Agilent Technologies, Inc., Santa Rosa, CA. Further contributions by the NRSC IBOC Standards Development Working Group. September 2008

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1. Introduction

The design of transmitters is constrained by the tension between cost and performance. With respect to transmitting digital signals, the cost of ownership and operation increases with the linearity required of the transmitter. This tension has a direct impact not only on the potential quality of the transmitted signal, but also on the generation and radiation of unwanted energy in the radio spectrum due to intermodulation. The In-Band/On-Channel ("IBOC") radio format known by the HD Radio™ brand name of iBiquity Digital Corporation requires only such transmitter linearity that is sufficient for transmitting a clean digital signal component in the presence of analog signals on the same and nearby channels.

Experimentally, the peak-to-average power ratio ("PAPR") of the digital IBOC FM signal at baseband is about 8 dB.[1] By the time it is modulated on an RF carrier and processed through power amplifiers it has been found to be reduced to about 4-6 dB. As a hybrid signal, when the digital is combined with the continuous wave analog FM signal, the envelope PAPR is between 1 and 2 dB.

There are numerous topologies for creating hybrid IBOC signals, particularly with FM IBOC. These involve various methods of generating and combining the digital and analog signals. On the AM IBOC side, hybrid signal generation is done with few variations in technique, but the high bandwidth-to-frequency ratio of the hybrid AM IBOC signal challenges the designer and operator with impedance matching and bandwidth issues. These can affect transmitter loading, system frequency and phase response, and pattern bandwidth.

The spectrum analyzer has been the instrument of choice for observing the hybrid IBOC system passband and for seeking potential spurious emissions. However, experience has shown that there can be differences in results obtained 1) with different analyzers, or 2) by different operators, or 3) at different signal sampling points, when examining the same signal. While most of these differences are minor, there have been situations where the differences result in opposing conclusions – a system's acceptance hangs in the balance as the conflicting results make it uncertain whether an installation passes or fails its RF mask compliance test.

The NRSC-5 standard, as amended from time to time, specifies a general technique for measuring the IBOC spectrum with a swept spectrum analyzer.[2] The technique involves taking an average of a series of spectrum sweeps that requires at least 30 seconds of data collection and at least 100 sweeps. The results of such averaging are dependent on how the selected spectrum analyzer works, on the settings that are chosen by the operator and on the location and method of sampling the signal. The 30-seconds/100-sweeps trace averaging method is a top-level description that is operational in nature. It presumes the test instrument is some type of swept analyzer and specifies three basic expectations for data collection. There is a trade-off between sweep rate, resolution bandwidth and frequency span that may challenge the dual requirement of 30 seconds and 100 sweeps in many circumstances. Further, analyzers may employ different

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[1] The IBOC Handbook, David Maxson, NAB/Focal Press 2007

[2] NRSC-5 Normative Reference Document #8, AM Transmission System Specifications, and #6, FM Transmission System Specifications.

methodologies that do not fit the traditional 30 seconds/100 sweeps model of data collection. For instance, a single long-term trace can be taken on some instruments, avoiding the need to average multiple traces, or an FFT analyzer might attack the measurement requirement differently than a swept analyzer.

1.1. Goals of this Paper

An emission specification must ensure that the IBOC transmission measurement meets its conflicting goals of accuracy, repeatability, cost and efficiency. A useful goal of a measurement specification is that it be “mathematically tractable.” A tractable specification is one that is defined in a way that its measurement can be made without dependence on the particular characteristics of a measuring device. This goal can be contrasted with an “operational definition.” An operational definition might describe how to configure a particular spectrum analyzer and evaluate the results against a measurement specification.

This paper presents a suggested tractable specification that supports the 30 second/100 sweep operational specification in the NRSC-5 transmission system specifications and that also leaves the opportunity for new instrumentation methods to be developed. The Guideline G-201 to which this paper is appended, presents the method that is operationally closest to the iBiquity specification adopted as reference documents in NRSC-5-B. This paper also provides further guidance on using spectrum analyzers and on a preferred means of sampling the IBOC signal.

2. Tractable and Suggested Operational Specifications for Hybrid IBOC Spectral Occupancy Measurements

In pure mathematical terms, power spectral density is often presented in the basic units of dBc/Hz. Such specifications describe pure power spectral densities per unit bandwidth. The unit bandwidth in this canonical form is not the same as a resolution bandwidth. It is an ideal bandwidth. Since resolution bandwidth filters are imperfect because they do not perfectly include the specified bandwidth and exclude all other frequencies, they present some error with respect to the ideal.

The importance of a tractable specification is that it is independent of any specific measurement instrument. The errors and uncertainties introduced by any specific instrument's filters can be described, linking the measurement results back to the tractable specification. On the contrary, when there is no tractable specification, one must assume that a specific instrument or instrument design is the reference against which all other measurement methods must be compared. The IBOC transmission system specifications do not describe a particular instrument architecture, thereby leaving to chance the variations in any engineer's measurement results.

2.1. Hybrid FM digital signal flatness and out-of band emissions: Specification 1— Tractable Definition

The power spectral density of the digital components of the hybrid FM IBOC signal and any out of band and spurious emissions should not exceed the RF mask in Figure 1. As expressed in Figure 1, in units of dBc per Hz, the mask is based on the ideal 1 Hz passband. No other filter characteristics are incorporated in this description. The reference level (0 dBc) for the mask shall be the power of the unmodulated analog FM carrier.

Frequency Offset Relative to Carrier	Power Spectral Density, dBc/Hz
100-200 kHz offset	-70
200-250kHz offset	[-91.4 – (|offset frequency kHz|-200) ·0.260]
250-540 kHz offset	-104.4
540-600 kHz offset	[-104.4 – (|offset frequency kHz|-540) ·0.093]
>600 kHz offset	-110

Table 1
Tractable Specification for Hybrid FM IBOC Power Spectral Density
In Decibels with Respect to Analog Carrier Power per Hertz of Bandwidth

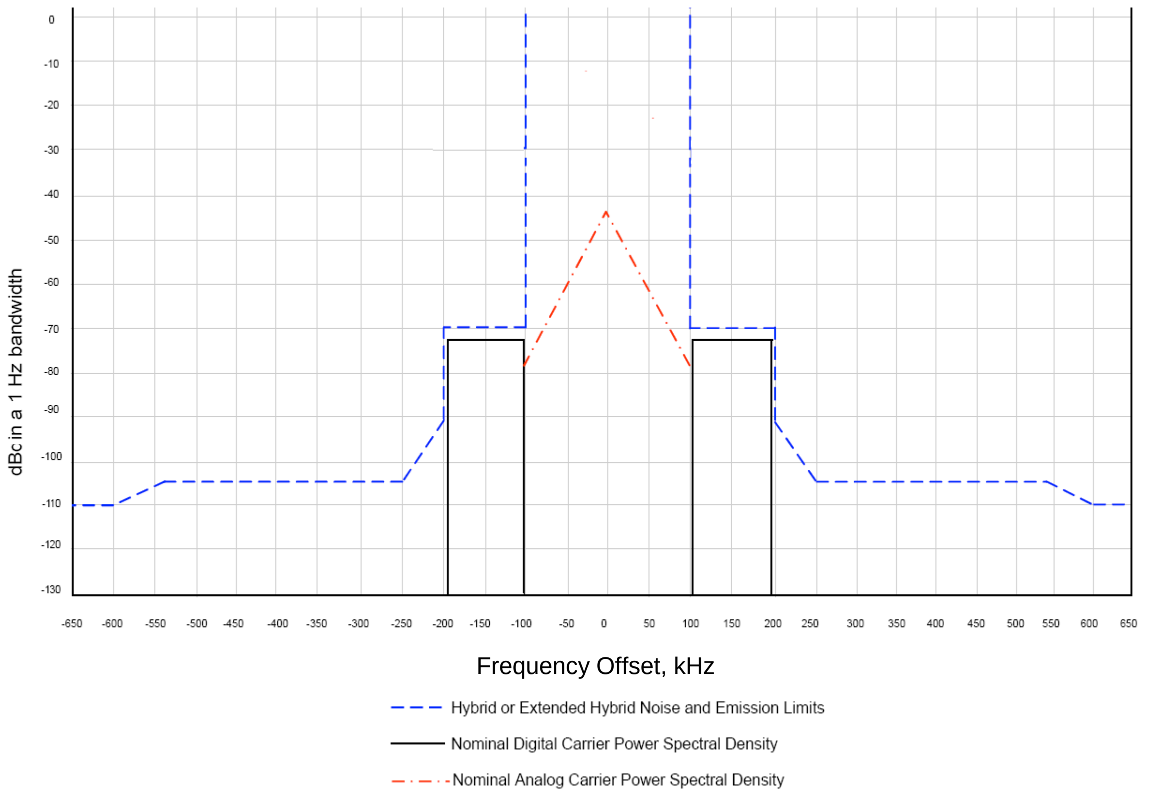

Figure 1
Tractable Specification for Hybrid FM IBOC Power Spectral Density
In Decibels with Respect to Analog Carrier Power per Hertz of Bandwidth

The tractable power spectral density mask may be scaled to compensate for the instrumentation employed, including such instrumentation characteristics as resolution bandwidth, RBW filter noise bandwidth, detector averaging error, and the like.

Obtaining adequate flatness across the 400 kHz passband of the hybrid FM IBOC signal is not typically a concern, due to the ability to maintain appropriate filter and antenna bandwidths at FM frequencies. The gain flatness of the radiated hybrid FM IBOC signal should be within ±0.5 dB, according to the standard. The group delay flatness is expected to be within 600 ns differential across the 400 kHz bandwidth. Group delay may be assumed to be in compliance when the group delay performance for all narrow band components (e.g. filters) in the transmission chain collectively meets this requirement.

2.2. Operational Variations: Bandwidth

When employing actual measurement and computational methods to determine compliance with this mask, it will be acceptable to employ bandwidths wider than the normalized 1 Hz bandwidth and to employ filter passband characteristics not matching the ideal, as long as the mask amplitude is adjusted accordingly.

For instance, employing a 1 kHz Resolution Bandwidth on a spectrum analyzer requires two adjustments to the tractable mask. First, the mask in Figure 1 is shifted +30 dB to compensate for the change from the tractable definition's ideal 1 Hz power spectral density to 1 kHz. (This results in the 1 kHz PSD mask adopted in NRSC-5.) Second, the mask should be shifted by an appropriate amount to compensate for the noise bandwidth of the actual filter employed by the analyzer.

An analog four-pole synchronous filter has a typical noise bandwidth that is 0.52 dB greater than the nominal (-3 dB) bandwidth of the filter. The increased bandwidth causes the four-pole filtered instrument to overstate the measured level of a noise-like signal by 0.52 dB. Employing a four-pole filter to measure IBOC signals requires an adjustment to the mask to account for the overstatement caused by the filtering technique. Hence, a measurement employing a 1 kHz four-pole filter requires a 30 + 0.52 = +30.52 dB adjustment to the mask. The uncertainty of the analog RBW will usually be 10 to 20%, thus giving an amplitude uncertainty of ±0.4 to ±0.8 dB

A Gaussian filter requires an adjustment on the order of +0.24 dB; with digitally implemented Gaussian filters, the uncertainty in the bandwidth is usually 0.5 to 1%, thus giving an amplitude uncertainty of ±0.02 to ±0.04 dB. See instrument specifications for the necessary filter corrections for noise-like signal measurements.

In addition to the filter noise bandwidth issue, the detection method can affect the result. If the swept spectrum analyzer lacks state-of-the-art digital detection and processing capability (the ability to average on a power scale, instead of a decibel scale), it will be necessary to decrease the mask by 2.51 dB to compensate for the analyzer's averaging error (e.g. +30.52 dB – 2.51 dB for 1 kHz RBW with conventional 4-pole filter and averaging error). Some older spectrum analyzers with "Sample" detectors have this error. However, other spectrum analyzers that have Sample detectors perform the averaging in a fashion that avoids the averaging error. The instrument operator must determine whether the instrument presents results with or without the error. Spectrum analyzers with "RMS" or "Average Power" detector capabilities are not expected to have this error.

In a swept analyzer, filter bandwidths greater than 1 kHz may be too wide in some circumstances to establish that an otherwise compliant signal is indeed in compliance with the FM IBOC mask, due to the spreading impact of filter bandwidths on the slopes of the mask. See further discussion in the section below titled Further Discussion of FM IBOC Measurements with Spectrum Analyzers.

2.3. Operational Variations: Reference Level

The reference method for establishing the analog carrier power level is with no modulation. With care, the analog carrier power can be measured reliably with modulation present. Attention should be paid to the manner in which a spectrum analyzer or other instrument integrates the total power of the modulated carrier; any corrections should be incorporated for the differences between such a measurement and measuring an unmodulated, continuous wave carrier.

Attention should also be given to the linear range of the spectrum analyzer input. All RF energy present at the input of the analyzer should total less than the 1 dB compression level of the instrument. If there are other signals on the spectrum (such as on a multi-station transmission line) it is the total power of all the signals that must not overload the instrument.

2.4. Operational Variations: Averaging Time

The tractable specification does not indicate an averaging time. Instead, one should sample the spectrum for a duration that is sufficient to minimize variations between sets of measurements that may be made at a later time. The minimum averaging time is dependent on the instrumentation and the span of frequencies being evaluated. To ensure sufficient averaging time, experience has shown that capturing at least 33 symbols per unit bandwidth results in relatively smooth traces. For less variance between measurements of the same signal, a longer acquisition time may be applied.

For example, a swept analyzer in power detection mode conducting a single sweep across 500 kHz of spectrum for 50 seconds crosses 1 kHz in 0.1 seconds. At the FM IBOC symbol rate of 344.5 Sy/s, the analyzer dwells for 34.45 symbols' duration in 1 kHz of spectrum, which is at least the suggested minimum 33 symbols per unit bandwidth.

In an alternative example, repeatedly sweeping a swept analyzer in power detection mode across the 500 kHz bandwidth at, say, 1 second per sweep[3] yields 0.69 symbols per kHz per sweep. Multiplied by 100 sweeps, the total symbol time per kHz of spectrum is 69 symbols, well above the recommended minimum.

On the other hand, an FFT analyzer that samples the entire frequency span of interest might provide repeatable results with a brief continuous digital sample of the RF signal. Sampling 33 successive symbols in this fashion would take about 1/10 second (Experimentation with this type of sampling suggests that the variance among successive measurements can be further reduced by increasing sampling time to 4/10 to 5/10 second.).

Other methods may be devised to achieve low variance between repeated measurements.

This guidance in sweep/averaging time can be employed with older spectrum analyzers, subject to correction of certain inherent errors or external computational analysis, or with newer spectrum analyzers with state-of-the-art power measurement capabilities, or with dedicated hardware designed for the purpose.

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[3] Operators are also advised to maintain the proper sweep rate for the selected resolution bandwidth. Using the minimum rule of thumb, the sweep rate (Hz/s) should be no faster than ½ times the square of the resolution bandwidth. Thus, a 500 kHz span should be swept at 1 kHz resolution bandwidth no faster than 1 second per sweep. Spectrum analyzers have auto-coupled sweep rates to ensure this criterion is met, so long as they are not disabled or their warnings ignored.

It is anticipated that application-specific devices may employ FFT techniques to develop mask measurements and signal statistics. The tractable specification enables instrument designers to employ the methods that best balance efficiency, accuracy, and repeatability without reliance on fixed bandwidths and "sweep" rates.

2.5. Measuring Hybrid FM IBOC Spectral Occupancy against the Mask:

The measurement of the spectral components of a Hybrid FM IBOC signal and potential out of band and spurious emissions is begun with the selection of a measurement device to make the measurement. The device should have low enough noise and high enough dynamic range to be able to discriminate signal and spurious emissions from the noise floor. This requires that the instrumentation noise floor be, for instance, less than -80 dBc/kHz for FM. It is recommended that the average noise floor be at least ten dB below the minimum level of the mask (e.g. -90 dBc/kHz for FM measured with a 1 kHz RBW). If the instrument noise floor is too high, it can add to a low-level spurious emission and make a mask-compliant emission appear non-compliant. Also, there should be some headroom between the total input power (average) of all RF energy on the input port and the 1 dB compression point of the instrument. If possible, allow 10 dB between the total input power to the first stage of the instrument (after passive attenuation) and the 1 dB compression level to insure that peaks, input level variations and minor calibration errors do not drive the input into compression.

Once the measurement device is selected, and if it has an adjustable resolution bandwidth, a desired RBW should be selected. The RBW should be no wider than the widest that is appropriate for the type of filter employed by the instrument. Wider RBWs permit faster data acquisition of the desired spectrum (such as sweeps of a swept analyzer), minimizing time spent on each measurement without compromising accuracy. Typical four-pole filters must be limited to 3 kHz RBW or less to keep within the FM mask slopes. Gaussian filters typically may be employed at up to 6.8 kHz RBW. These limits are based on how the slopes of these filters interact with the slopes of the hybrid FM IBOC RF mask.

- The following adjustments to the mask may be required depending on the nature of the instrument selected:

  The mask in this paper is presented in dBc/Hz. Raise the mask (or deduct from the measured value) to account for the actual bandwidth of the displayed result before comparing results with the mask. The conversion from dBc/Hz to dBc/kHz is 30 dB. For dBc/3 kHz to dBc/Hz, the conversion is 34.8 dB. If the instrument can report results in dBc/Hz (literally with 1 Hz RBW filtering, or by mathematical conversion when using other filter bandwidths), then the mask need not be adjusted to compensate for the chosen bandwidth.

  Raise the mask (or deduct from the measurement) 0.52 dB for the noise bandwidth of four-pole synchronously tuned RBW filters, or 0.24 dB for Gaussian filters, or the number of dB specified by the manufacturer to adjust for the noise bandwidth of the filter in use. If the manufacturer indicates that the instrument makes the filter noise bandwidth correction internally, then do not manually make an adjustment.

- Set input levels and for less than the nominal compression level of the instrument. Keep in mind the presence of other strong signals on the signal source that might contribute to the instrument's compression of the signal under test.

- Set the reference level by measuring the FM carrier level. The reference method is to cut modulation, however upon verification of results it may suffice to use a wide (100 kHz, 300 kHz or 1 MHz RBW) filter, and averaging if needed, to ascertain the reference level.

  On an instrument that has no true power detection feature (such as older spectrum analyzers with a sample detector that requires trace averaging to measure digital signals) there may be a discrepancy of up to 2.5 dB between the displayed and the actual IBOC sideband power. In such cases, sample detection with log display and trace averaging of the digital signal can understate the digital sideband power by up to 2.5 dB while the analog continuous wave reference signal is measured without such a bias. Caution, some analyzers with sample detection and trace averaging make the necessary corrections by not averaging the traces but averaging the underlying data, in which case this error is not present. The operator must be familiar with the instrument's averaging method to make the correct adjustments.

- Set the desired display span, if the instrument permits. Ensure the display span is narrow enough to maintain frequency accuracy.

- Establish the data accumulation time. Ensure that the total time spent in the working bandwidth (e.g. RBW) or the data sampling time (e.g. for an FFT analysis) amounts to at least 33 symbols (approx 0.1 seconds) per unit bandwidth. More may be necessary to achieve the desired reduction in variance. Multiply this by the span to obtain the sweep time, or other data accumulation time, required.

Conduct one or more measurements of the signal.

2.6. Measuring Hybrid FM digital signal subcarrier group power (i.e. Primary Main, Primary Extended upper or lower sidebands):

The measurement of subcarrier group power is a means to quickly determine that the ratios between analog power and the injected power of the various IBOC subcarrier groups is correct. This measurement has no independent tractable component because it is derived from the tractable specification for hybrid FM operation (Specification 1) and from the Amplitude Scale Factors of the subcarriers. It is presented to provide guidance on measuring total power within the hybrid FM IBOC digital sidebands.

Hybrid Mode	**MP1**	**MP2**	**MP2**	**MP3**	**MP11**
Subcarrier groups	Primary Main	Primary Main + Primary Extended 1	Primary Main + Primary Extended 1& 2	Primary Main + Primary Extended 1, 2 & 3	Primary Main + Primary Extended 1, 2, 3 & 4
Passband Start Frequency Offset	129179 Hz	122275	115371	108467	101563
Passband Stop Frequency Offset	198583 Hz	198583	198583	198583	198583
Maximum power per sideband (upper or lower)	-21.6 dBc	-21.1	-20.8	-20.4	-20.1
Nominal power per sideband	-23 dBc	-22.5	-22.2	-21.8	-21.5

Table 2
Passbands, Nominal Levels, and Maximum Levels of Hybrid FM IBOC Primary Main, and Primary Extended OFDM Subcarrier Groups

The combined power of the Primary Main (“PM”) hybrid digital subcarrier sidebands are expected to be nominally ≤-20 dBc (or -23 dBc per sideband). For additional Primary Extended subcarrier partitions, see the computed nominal power levels and corresponding measurement passbands in Table 2. Recommended maximum power levels, based on Specification 1, are presented in Table 2. Actual measurements should be adjusted to compensate for the differences between the measurement method and the ideal values provided in Table 2.

Example— Spectrum Analyzer Total Channel Power Measurement of Hybrid FM IBOC Digital Subcarrier Groups.

There are two bandwidth settings to consider. First, set the Channel Power bandwidth to be measured to 100 kHz. This will cover one full sideband of Primary Main and Primary Extended subcarriers. Center the 100 kHz Channel Power bandwidths of each measurement at −150 and +150 kHz (lower and upper sideband measurements, respectively) relative to the carrier. If the instrument requires the selection of an RBW narrower than the channel span of interest, then set the optimum Resolution Bandwidth for the instrument to employ to integrate across the Channel Power bandwidth. To obtain a measurement of all the subcarriers in one sideband with Gaussian RBWs, as noted above, the RBW can be set as wide as 6.8 kHz, or narrower. With the four-pole synchronously tuned filters, the widest RBW that will enable a tight Channel Power measurement limited to the Primary sideband is 3 kHz.

These settings will still allow for center frequency errors of 1 kHz. For an analyzer with 0.25%-of-span "frequency readout accuracy," the span may be up to 400 kHz for this measurement, thus one sweep and two positionings of a "band marker" can make the measurement conveniently and with the required accuracy. Be certain analog modulation does not corrupt the measurement; keep analog sidebands from dominating the -3 to -30 dB slope of the RBW filter or substantially overlapping into the passband of the measurement.

2.7. Further Discussion of FM IBOC Measurements with Spectrum Analyzers

Numerical modeling[4] for older spectrum analyzers with 4-pole sync-tuned filters shows that the response of a channel bandwidth computation has 30 dB rejection at an offset 2.079 RBWs from the edge of the channel. Thus, a 3 kHz RBW will have at least 30 dB rejection to show mask conformance. In contrast, a 10 kHz RBW may not.

The four-pole filter passband flatness is -3 dB at the nominal bandwidth and within 0.5 dB from 0.589 RBWs inward.

For Gaussian RBW filters, the response of a channel bandwidth computation has 30 dB rejection at an offset 1.312 RBWs from the edge of the channel. Thus, a 6.8 kHz RBW meets the 30 dB rejection objective at the sides of the passband while still allowing a margin for frequency accuracy of 1 kHz.

The passband flatness of a Gaussian RBW filter is within 0.5 dB from 0.524 RBWs inward.

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[4] Acknowledgement is given to Mr. Joe Gorin of Agilent for providing analysis of spectrum analyzer filter performance and other valuable assistance in generating this document.

3. AM

In pure mathematical terms, power spectral density is often presented in the basic units of dBc/Hz. Such specifications describe pure power spectral densities per unit bandwidth. The unit bandwidth in this canonical form is not the same as a resolution bandwidth. It is an ideal bandwidth. Since resolution bandwidth filters are imperfect because they do not perfectly include the specified bandwidth and exclude all other frequencies, they present some error with respect to the ideal.

The importance of a tractable specification is that it is independent of any specific measurement instrument. The errors and uncertainties introduced by any specific instrument's filters can be described, linking the measurement results back to the tractable specification. On the contrary, when there is no tractable specification, one must assume that a specific instrument or instrument design is the reference against which all other measurement methods must be compared. The IBOC transmission system specifications do not describe a particular instrument architecture, thereby leaving to chance the variations in any engineer's measurement results.

3.1. Hybrid AM digital signal flatness and out-of band emissions: Specification 2 – Tractable Definition

The power spectral density of the digital components of the hybrid AM IBOC signal and any out of band and spurious emissions should not exceed the RF mask in Figure 2. As expressed in Figure 2, in units of dBc per Hz, the mask is based on the ideal 1 Hz passband. No other filter characteristics are incorporated in this description. The reference level (0 dBc) for the mask shall be the power of the unmodulated analog AM carrier.

Frequency Offset Relative to Carrier	**Power Spectral Density, dBc/Hz**
5-10 kHz offset*	-59.1
10-15 kHz offset	-51.6
15-15.2 kHz offset	-52.8
15.2-15.8 kHz offset	-63.8 – (|offset frequency kHz|-15.2) ·43.3
15.8-25 kHz offset	-89.8
25-30.5 kHz offset	-89.8 – (|offset frequency kHz|-25) ·1.273
30.5-75 kHz offset	-96.8 – (|offset frequency kHz|-30.5) ·0.292
>75 kHz offset	-109.8

Table 3

Tractable Specification for Hybrid AM IBOC Power Spectral Density

In Decibels with Respect to Analog Carrier Power per Hertz of Bandwidth

*This table assumes AM analog operation at 5 kHz audio bandwidth; for the 8 kHz option, this entry changes to "8-10 kHz offset" to accommodate the presence of analog sideband energy between 5 and 8 kHz offsets.

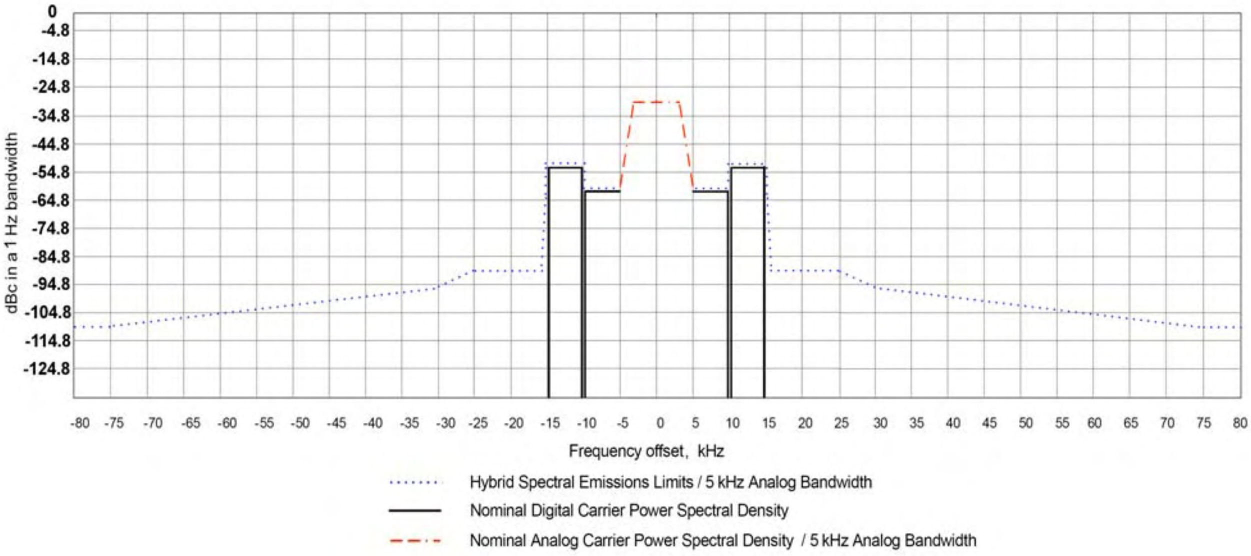

Figure 2
Tractable Specification for Hybrid AM IBOC Power Spectral Density
In Decibels with Respect to Analog Carrier Power per Hertz of Bandwidth

Further, it is recommended that the Hybrid AM IBOC signal be transmitted with an amplitude flatness ±0.5 dB to 10 kHz off center and ±1 dB to 15 kHz.[5] NRSC-5-B cals for phase response to be within ±3 μs across the 30 kHz spectrum of the signal[6], with the antenna system optimized for Hermitian symmetry. Recognizing that some AM antenna systems may not be able to fully comply with this flatness criterion, this flatness specification is advisory.

3.2. Operational Variations: Bandwidth

When employing actual measurement and computational methods to determine compliance with this mask, it will be acceptable to employ bandwidths wider than the normalized 1 Hz bandwidth and to employ passband characteristics not matching the ideal, as long as the mask amplitude is adjusted accordingly.

For instance, employing a 300 Hz resolution bandwidth on a spectrum analyzer requires two adjustments to the mask. First, the tractable mask is shifted +24.8 dB to compensate for the change from the tractable definition's 1 Hz power spectral density to 300 Hz. Second, if applicable, the mask should be shifted by an appropriate amount to compensate for the noise bandwidth of the actual filter employed by the analyzer. A traditional physical four-pole synchronous filter has a typical noise bandwidth that is 0.52 dB greater than the ideal bandwidth

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[5] NRSC-5-B specifies these figures. On the contrary iBiquity suggests in the NAB Engineering Handbook, 10th edition, that the specification be ±0.5 dB to 5 kHz and ±4 dB to 15 kHz.

[6] NRSC-5-B specifies this. In the NAB Engineering Handbook, 10th edition, the suggested figure is 5 μs.

of the same nominal value. The increased bandwidth causes the four-pole filtered instrument to overstate the measured level of a noise-like signal by 0.52 dB. Employing a four-pole filter to measure IBOC signals requires an adjustment to the mask to account for the overstatement caused by the filtering technique. Hence, a measurement employing a 300 Hz four-pole filter requires a 24.8 + 0.52 = +25.4 dB adjustment to the Figure 2 mask.

A Gaussian filter would require a correction of +0.27 dB; typical digitally implemented approximations to a Gaussian filter require no correction.

In a swept analyzer, 4-pole filter bandwidths greater than 300 Hz may be too wide to establish that an otherwise compliant signal is indeed in compliance with the mask, due to the spreading impact of filter bandwidth on the slopes of the mask. See further discussion in the section below titled Further Discussion of AM IBOC Measurements with Spectrum Analyzers.

3.3. Operational Variations: Reference Level

The reference method for establishing the analog carrier power level is with no modulation. With care, the analog carrier power can be measured with modulation present. Even with asymmetrically modulated AM signals (e.g., +125/-99%) the average power of the carrier, as measured with a narrow RBW (e.g. ≤300 Hz) is typically a reliable indicator of the carrier power reference. Attention should be paid to the manner in which a spectrum analyzer or other instrument integrates the total power of the modulated carrier; any corrections should be incorporated for the differences between such a measurement and measuring an unmodulated, continuous wave carrier.

3.4. Operational Variations: Averaging Time

The tractable specification does not indicate an averaging time. Instead, one should sample the spectrum for a duration that is sufficient to minimize variations in successive measurements. The minimum averaging time is dependent on the instrumentation and the span of frequencies being evaluated. To ensure sufficient averaging time, experience has shown that capturing at least 33 symbols per unit bandwidth results in relatively smooth traces. For less variance between measurements of the same signal, a longer acquisition time may be applied.

For example, a swept analyzer in power detection mode sweeping 40 kHz of spectrum once for 30 seconds crosses 300 Hz in 0.23 seconds. At a symbol rate of 172.3 Sy/s, the analyzer dwells for 39 symbols' duration in 300 Hz of spectrum, which is at least 33 symbols, as recommended.

In an alternative example, repeatedly sweeping a swept analyzer in power detection mode across the 40 kHz bandwidth at, say, 1 second per sweep[7], yields 1.3 symbols per 300 Hz per sweep. Multiplied by 30 sweeps, the total symbol time per 300 Hz of spectrum is 39 symbols.

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[7] Operators are also advised to maintain the proper sweep rate for the selected resolution bandwidth. Using the minimum rule of thumb, the sweep rate (Hz/s) should be no faster than ½ times the square of the resolution bandwidth. Thus, a 45 kHz span should be swept at 300 Hz resolution bandwidth no faster than 1 second per sweep. Spectrum analyzers have auto-coupled sweep rates to ensure this criterion is met, so long as they are not disabled or ignored.

On the other hand, an FFT analyzer that samples the entire frequency span of interest might provide repeatable results with a brief continuous digital sample of the RF signal. Sampling 33 successive symbols in this fashion would take about 1/5 second (Experimentation with this type of sampling suggests that the variance among successive measurements can be further reduced by increasing sampling time to 4/5 to 1 second.).

Other methods may be devised to achieve low variance between repeated measurements.

This guidance can be employed with older spectrum analyzers, subject to correction of certain inherent errors or external computational analysis, or with newer spectrum analyzers with state-of-the-art power measurement capabilities, or with dedicated hardware designed for the purpose.

It is anticipated that application-specific devices may employ FFT techniques to develop mask measurements and signal statistics. The tractable specification enables instrument designers to employ the methods that best balance efficiency, accuracy, and repeatability without reliance on fixed bandwidths and "sweep" rates.

3.5. Measuring Hybrid AM IBOC Spectral Occupancy against the Mask:

The measurement of the spectral components of a Hybrid FM IBOC signal and potential out of band and spurious emissions is begun with the selection of a measurement device to make the measurement. The device should have low enough noise and high enough dynamic range to be able to discriminate signal and spurious emissions from the noise floor. This requires that the instrumentation noise floor be, for instance, less than -85 dBc/300 Hz for AM. It is recommended that the average noise floor be at least ten dB below the minimum level of the mask (e.g. -95 dBc/300 Hz for AM measured with a 300 Hz RBW). If the noise floor is too high, it can add to a low-level spurious emission and make a mask-compliant emission appear non-compliant.

Once the measurement device is selected and if it has an adjustable resolution bandwidth, select the widest appropriate RBW, based on the type of filter employed by the instrument. Wider RBW's permit faster data acquisition of the desired spectrum (such as sweeps of a swept analyzer), minimizing time spent on each measurement without compromising accuracy. Typical four-pole filters must be limited to 300 Hz RBW's or less. Gaussian filters may be employed at 1 kHz RBW.

- The following adjustments to the mask may be required depending on the nature of the instrument selected:

  The mask is presented in dBc/Hz. Raise the mask (or deduct from the measured value) to account for the actual bandwidth of the displayed result before comparing results with the mask. The conversion from dBc/Hz to dBc/kHz is 30 dB. For dBc/300 Hz the conversion is 24.8 dB. If the instrument can report results in dBc/Hz, then the mask need not be adjusted to compensate for the chosen bandwidth.

Raise the mask (or deduct from the measurement) 0.52 dB for four-pole synchronously tuned RBW filters, or 0.24 dB for Gaussian filters, or the number of dB specified by the manufacturer to adjust for the noise bandwidth of the filter in use. If the manufacturer indicates that the instrument makes the filter noise bandwidth correction internally, then do not manually make an adjustment.

- Set input levels and for less than the nominal compression level of the instrument. Keep in mind the presence of other strong signals on the signal source that might contribute to the instrument's compression of the signal under test.

- Set the reference level by measuring the AM carrier level. The reference method is to cut modulation, however upon verification of results it may suffice to use a narrow filter and averaging to ascertain the reference level.

  On an instrument that has no true power detection feature (such as older spectrum analyzers with a sample detector that requires trace averaging to measure digital signals) there may be a discrepancy of up to 2.5 dB between the use of an unmodulated carrier reference and the use of trace averaging to measure digital signal power spectral density. In such cases, this type of detection and averaging of the digital signal understates the digital power on a logarithmic detector by up to 2.5 dB while the analog Continuous Wave reference signal is measured without such a bias.

- Set the desired display span, if the instrument permits. Ensure the display span is narrow enough to maintain frequency accuracy.

- Establish the data accumulation time. Ensure that the total time spent in the working bandwidth (e.g. RBW) or the data sampling time (e.g. for an FFT analysis) amounts to at least 33 symbols (approx 0.2 seconds) per unit bandwidth, or more if necessary to reduce measurement variance. Multiply this by the span to obtain the sweep, or other data accumulation, time required.

Conduct one or more measurements of the signal.

3.6. *Measuring Hybrid AM digital signal subcarrier group power (i.e. Primary, Secondary, and Tertiary upper or lower sidebands):*

The measurement of subcarrier group power is a means to quickly determine that the ratios between analog power and the injected power of the various IBOC subcarrier groups is correct. The measurement of subcarrier group power has no independent tractable component because it is derived from the tractable specification for hybrid AM operation (Specification 2) and from the Hybrid AM IBOC OFDM amplitude scale factors in the NRSC-5 Reference Documents. It is presented to provide guidance on measuring total power within each of the hybrid AM IBOC digital sidebands.

Recommended maximum power levels, based on Specification 2, are presented in Table 4. Actual measurements should be adjusted to compensate for the differences between the measurement method and the ideal values provided in Table 4.

AM IBOC Hybrid Mode	High Power Option		
Subcarrier groups	Primary	Secondary	Tertiary
Passband Start Frequency Offset	10 kHz	5	0.2*
Passband Stop Frequency Offset	15 kHz	10	5
Maximum power per sideband (upper or lower)	-15 dBc	-22.5	-29.5
Nominal power per sideband	-16 dBc	-23	-30

Table 4
Passbands, Nominal Levels, and Maximum Levels of Hybrid AM IBOC Primary, Secondary, and Tertiary OFDM Subcarrier Groups

* Nominal offset to minimize impact of unmodulated analog carrier and Reference subcarriers.

**These specifications are the same for 5- and 8-kHz analog audio bandwidth systems, except that more care must be taken to limit analog AM sidebands in the 5-10 kHz offset region during measurements of the Secondary subcarriers.

Example— Spectrum Analyzer Total Channel Power Measurement of Hybrid AM IBOC Digital Subcarrier Groups.

There are two bandwidth settings to consider. First, set the Channel Power bandwidth to be measured to 5 kHz. This will cover one of the OFDM subcarrier sideband groups. Center the 5 kHz Channel Power bandwidths of each measurement at −12.5, -7.5, +12.5, and +7.5 kHz (Primary and Secondary, lower and upper sideband groups, respectively) relative to the carrier. The Tertiary sidebands reside beside the AM carrier and beneath the AM modulation, so a total power measurement of the Tertiary sidebands' energy is not obtained with a typical spectrum analyzer unless modulation is removed. Then set the optimum Resolution Bandwidth for the instrument to employ to integrate across the Channel Power bandwidth. To obtain a measurement of all the subcarriers in one sideband with Gaussian RBWs, as noted above, the RBW can be set as wide as 1 kHz, or narrower. With the four-pole synchronously tuned filters, the widest RBW that will enable a Channel Power measurement that will not fail on the mask slope is 300 Hz RBW.

3.2. Further Discussion of AM IBOC Measurements with Spectrum Analyzers

Numerical modeling for older spectrum analyzers with 4-pole sync-tuned filters shows that the response of a channel bandwidth computation has 30 dB rejection at an offset 2.079 RBWs from the edge of the channel. Thus, a 300 Hz RBW will have at least 30 dB rejection necessary to show mask conformance. In contrast, a 4-pole 1 kHz RBW filter will not. This is a particularly challenging situation due to the relative steepness of the Hybrid AM IBOC mask slopes, compared to the FM Hybrid IBOC mask. The AM mask is just useable with four-pole filters when scaled up to 300 Hz power spectral density because the slope outside the OFDM subcarrier frequencies approximates that of a 300 Hz four-pole synchronously tuned spectrum analyzer filter measuring an ideally modulated Primary sideband.[8]

The four-pole filter passband flatness is -3 dB at the nominal bandwidth and within 0.5 dB from 0.589 RBWs inward. Thus, a 300 Hz RBW would meet the passband flatness requirement from 10.18 kHz to 14.82 kHz.

For Gaussian RBW filters, the response of a channel bandwidth computation has 30 dB rejection at an offset 1.312 RBWs from the edge of the channel. Thus, a Gaussian 1 kHz Hz RBW meets the rejection objective of the mask at the sides of the OFDM subcarrier passband.

The passband flatness of a Gaussian RBW filter is within 0.5 dB from 0.524 RBWs inward. Thus, a 1 kHz Gaussian RBW would meet the passband flatness requirement from 10.53 kHz to 14.47 kHz. With Gaussian RBWs, the RBW can be set to 1 kHz or narrower, while still allowing for frequency errors of 188 Hz. For an analyzer with 0.25%-of-span “frequency readout accuracy,” the span may be up to 75 kHz for this measurement, thus one sweep and two positionings of a “band marker” can make the Primary Sideband total power measurements conveniently and with the required accuracy.

The process may be repeated at -7.5 and +7.5 kHz offsets relative to the carrier to obtain the Secondary Sideband measurements from -5 to -10 kHz and +5 to +10 kHz. Be certain analog modulation does not corrupt the measurement; keep analog sidebands from dominating the -3 to -30 dB slope of the RBW filter or substantially overlapping into the passband of the measurement.

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[8] Maxson, D., The Role of The Detector in Spectrum Analyzer Measurement of Digital Signals, National Association of Broadcasters 2008 Broadcast Engineering Conference Proceedings

4. Discussion of Spectrum Analyzer Measurements

4.1. Making Measurements to the Standards with Newer Spectrum Analyzers

Newer spectrum analyzers have capabilities and convenience features that allow these kinds of measurements to be made easily and accurately. Ideally, an analyzer has a power-responding detector or suitable work-around, and a power-integrating marker or measurement function.

The power-responding detector is often called an “RMS detector” because it responds proportionally to the mean-square of the changing voltage of the signal, in other words, proportionally to the power. Manufacturers also may call this detector the “average detector” or “average detector: power” because it responds to the average of a signal parameter within a short duration; with this detector, the user has the choice of whether to average the voltage, the log of the voltage, or, as desired in this case, the power. Care should be taken to set the video bandwidth (VBW) of the analyzer much wider than the resolution bandwidth (RBW); this is necessary because the VBW filter typically operates on the display scale, which is usually set to a log scale, and averaging on the log scale does not achieve the correct result for noise-like signals.

A specialized “power integrating” feature of the digital spectrum analyzer is often called a “channel power measurement” or a “band power marker.” These measure the power across some width of the spectrum analyzer display by summing the measurement points (sometimes called “buckets” or “pixels”) and correcting for the effects of the point spacing and the noise bandwidth of the RBW being used.

Some modern analyzers have RBW filters with much higher selectivity than the 4-pole filters that have traditionally been commonplace. Higher selectivity allows wider RBWs to be used without polluting the desired measurement band with adjacent spectral energy, and alternatively without causing a measured signal to appear to exceed a steep mask slope. The variance of a power measurement of a noise-like signal is inversely proportional to the bandwidth, so such a modern analyzer can make measurements proportionally faster for a constant variance in results.

4.2. Making Measurements to the Standards with Older Spectrum Analyzers: Exact but Inconvenient Techniques

As mentioned above, older analyzers may not have suitable detectors, suitable “channel power” functions or markers, or high selectivity RBWs.

If the older analyzer does not have channel power functions, some instruments permit the trace data to be exported to an external computer which can be programmed to make a computation and incorporate the necessary adjustments..

Finally, without an RMS-style detector, the best measurement technique is to use a VBW of 10 or more times the RBW. The "Sample" detector should be used with multi-sweep averaging of the results in linear power units. This technique will allow power-scale response whether the channel power summation is done with an internal or external computation.[9]

4.3. Making Measurements to the Standards with Older Spectrum Analyzers: Inexact but Convenient Technique

Older analyzers do not have power-scale averaging processes, such as the RMS detector. They average signal, whether with the VBW filter or trace averaging, on the "display scale" of the analyzer. Usually, this scale is set to a logarithmic scale, such as 10 dB/division, but can be set to the "linear" (linear in volts, that is) scale. Neither of these scales is linear in power.

If the signal being measured has a statistical distribution that is assured to be noise-like, the response of the analyzer due to its averaging on the log scale is well known to be an under-response of 2.506 dB. Therefore, heavy filtering from trace averaging or VBW filtering can be used, and the analyzer response can be compensated by adding 2.506 dB to the result. If there is a CW-like spurious signal dominating the measurement, though, this technique will overcorrect for the average power of the CW signal. The error on the spurious CW signal is in the direction that makes a device-under-test more likely to fail with such an interfering signal, and thus would not increase the risk of passing a device that should have failed. So this error source might be an acceptable compromise for the convenience of averaging in the older spectrum analyzer.

4.3.1. How Close to Gaussian is the IBOC Digital Signal?

It turns out to be an excellent approximation to assume that the IBOC digital signal is white noise-like (Gaussian in its amplitude-over-time distribution). Experiments with OFDM signals with properly scaled RBW filters shows that the error in averaging the logs of a series of samples within a given bandwidth is nearly identical to the error that would occur with a purely Gaussian noise signal. The log average of the IBOC signal in the 1 kHz RBW (300 Hz for AM) was 0.04 dB higher than predicted for a Gaussian signal. Thus, the user of older analyzers who employs the 2.506 dB adjustment for noise-like modulation will see shrinkage of the margin by only 0.04 dB. In fact, if rounded to the nearest 1/10 dB, which is common in field measurements of broadcast signals, the Gaussian error and the IBOC error in making log averages is indistinguishable.

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[9] The computation is fairly straightforward: sum the powers (e.g., in mW, not dBm) of all the data points in the passband; divide by the number of data points in the passband; divide by the effective noise bandwidth of the RBW filter; multiply by the bandwidth of the passband. See, for example, Agilent Technologies, Inc., Application Note 1303, Spectrum Analyzer Measurements and Noise, for details on this computation.

4.4. Averaging Techniques

This Section discusses the tradeoffs between trace averaging and video filtering, and between longer sweeps and trace averaging.

4.4.1. Trace Averaging vs. Video Filtering

Trace averaging acts to reduce the variance of spectrum analyzer results that vary on a trace-by-trace time scale. Video filtering acts to reduce the variance when the results vary within the time scale associated with sweeping through a resolution bandwidth filter. (It is beyond the scope of this discussion to consider the tradeoffs in FFT-based, rather than sweep-based, spectrum analyzers, but the conclusions are similar.)

If the signal is incoherent with the sweeping, as digital modulations are always expected to be, then the two forms of variance reduction are similarly effective. There is a subtle tradeoff between throughput and convenience. The manual user often prefers trace averaging because an approximation to his final result appears very early in the averaging process as he watches it accumulate. The remote user often prefers a narrow VBW filter because the overhead of "retrace" (starting a new sweep) occurs only once, improving throughput. By experimentation it has been shown that use of the trace average on IBOC signals gives a crisper, more readily interpreted result than VBW filtering.[10] It is recommended that for IBOC measurements a trace-averaged or long-period single trace measurement be employed instead of video filtering. In this case, the VBW filter should be set to be wider than the resolution bandwidth.

This throughput and convenience tradeoff is not available to the user making "channel power" measurements on a power scale with an external computer attached to an analyzer. If the trace is filtered with a VBW filter operating on the decibel scale before being transmitted to an external computer trying to achieve power response by power summing individual elements, the effect of the VBW averaging on the decibel scale is to cause errors up to 2.51 dB. This defeats one of the purposes of removing trace data from the analyzer for external processing— performing computations on the power scale instead of the log scale or voltage scale.

4.4.2. Long Sweep Versus Trace Averaging

There is also a subtle tradeoff between long sweeps and trace averaging that applies when an RMS detector is in use. As in the case with the VBW filter acting on each sweep point, the average detector averages the signal power across the duration of each data point on the sweep ("bucket"). As long as the signal is noise-like or otherwise not coherent with the sweeping, the user can either spend more time on each point, or take more sweeps, and in both cases, get the same reduction in variance.

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[10] David Maxson, Measuring Your IBOC Spectrum, NAB Radio Show, 2004

Depending on the implementation of the manufacturer, the average power detector in multi-trace averaging might simply average a series of traces, yielding an averaging error, albeit minor[11], or it might, more appropriately perform a power computation on the raw data of the accumulated series of sweeps to obtain a more accurate trace-averaged power reading. It may be difficult to get an answer, with certainty, from a manufacturer as to what method the analyzer uses to trace-average in RMS or power detector mode.

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[11] When an average detector is employed, the error in trace averaging is substantially reduced, compared to the 2.51 dB error when trace averaging with a sample detector. This is because the average detector already has taken an average power measurement of numerous data points in each bucket, thus reducing the "noisiness" of each of the average power detector data points that are subsequently averaged together.

ANNEX 2

NRSC-G201, NRSC-5 RF Mask Compliance: Measurement Methods and Practice Test and Measurement Equipment Self-Certification List

UPDATED November 13, 2009

The test and measurement equipment listed in this Annex has been **self-certified by the manufacturer** as being suitable for determining if an RF signal is compliant with the NRSC-5 AM IBOC and/or FM IBOC emission masks. The manufacturers of all equipment listed herein have completed the form included in Annex 3 of the Guideline and submitted it to the NRSC, requesting inclusion in this list. An updated list is published as new items are added.

Neither the NRSC nor its members, participants or co-sponsors make any claim as to the suitability of this equipment for use in making the RF mask compliance measurements described in the NRSC-G201 Guideline. Parties interested in making these measurements need to verify for themselves that this equipment is in fact suitable for their measurement needs.

Anyone wishing to provide information to the NRSC as to the suitability or unsuitability of this equipment for IBOC RF mask compliance measurements should send an email to nrsc@nab.org. Please include in this email the manufacturer's name and equipment model number of the unit(s) being discussed.

(continued on next page)

Annex 2 – NRSC-G201 NRSC-5 RF Mask Compliance: Measurement Methods and Practice – Test and Measurement Equipment Self-Certification List – UPDATED November 13, 2009

	Manufacturer					Self-certified for:		
No	**Name**	**Website**	**Model**	**Description**	**Date of self-certification**	**AM IBOC**	**FM IBOC**	**Supports IBOC mask limit lines?**
1	Anritsu	www.us.anritsu.com	MS2034A, MS2036A	VNA Master (with spectrum analyzer)	5/19/09	✓	✓	Yes
			MS2717B, MS2718B, MS2719B, MS2721B, MS2723B, MS2724B	Spectrum analyzer	5/19/09	✓	✓	Yes
			MT8221B	Spectrum analyzer	7/8/09	✓	✓	Yes
2	Agilent Technologies	www.agilent.com	N9340B w/option IBC,	Spectrum analyzer	5/19/09	✓	✓	Yes (built-in)
			ESA series (E4402B, E4403B, E4404B, E4405B, E4407B, E4408B, E4411B), EXA series (N9010A)	Spectrum analyzer	5/19/09	✓	✓	Yes
3	Tektronix	www.tek.com	RSA3303B, RSA3308B, RSA3408B	Spectrum analyzer	9/18/09	✓	✓	Yes
			RSA6106A, RSA6114A, RSA6120A	Spectrum analyzer	9/18/09		✓	Yes
4	LP Technologies, Inc.	www.lptech.com	LPT-3000, LPT-3000R	Spectrum analyzer	11/5/09	✓	✓	Yes

ANNEX 3 – Test and Measurement Equipment Self-certification Form

NATIONAL RADIO SYSTEMS COMMITTEE

NRSC-G201, NRSC-5 RF Mask Compliance: Measurement Methods and Practice Test and Measurement Equipment Self-Certification Form

Please submit completed form to:

National Association of Broadcasters
1771 N Street, N.W.
Washington, DC 20036
Attn: Science & Technology Department

Email: nrsc@nab.org
Fax: 202-775-4981

This form is for manufacturers of test and measurement equipment suitable for determining if an RF signal is compliant with the NRSC-5 AM IBOC and FM IBOC emission masks, in accordance with the measurement techniques discussed in the NRSC-G201 Guideline. Please complete this form and submit it to NAB by mail, fax, or email, using the contact information above.

Completed forms will be reviewed by the NRSC and if found complete, the equipment described therein will be added to Annex 2 of the NRSC-G201 Guideline, which lists test and measurement equipment that has been self-certified by the manufacturer as being suitable for IBOC mask compliance measurements.

Company information:

COMPANY			
NATURE OF YOUR BUSINESS			
ADDRESS			
CITY		STATE	ZIP CODE
PHONE (MAIN NUMBER)	FAX	WEBSITE	

Contact information:

NAME			
TITLE			
ADDRESS			
CITY		STATE	ZIP CODE
PHONE	FAX	EMAIL ADDRESS	

Test and measurement equipment description (use a separate page 2 of this form for each model being self-certified):

MODEL NUMBER	(OPTIONAL) VERSION
SELF-CERTIFYING FOR: ☐ AM IBOC ☐ FM IBOC	
DESCRIPTION: ☐ SPECTRUM ANALYZER ☐ MODULATION ANALYZER ☐ OTHER ____________________	
FORM FACTOR: ☐ HAND-HELD ☐ PORTABLE ☐ RACK-MOUNTABLE ☐ OTHER ____________________	

Is there a “Tech Note” for this model which discusses IBOC mask compliance measurements? ☐ YES ☐ NO
If YES, please provide a reference to this Tech Note (URL preferred):

____

Does instrument support the use of limit lines for FM , AM IBOC masks (see Section 6.1.5 of NRSC-G201)? If so, please describe here:

____

____

Self-certification items –check off all that apply:

Hybrid AM IBOC mask compliance measurements (check off each item to certify compliance):

☐ Minimum frequency range: 400 kHz –2 MHz
☐ Resolution bandwidth (RBW) settable to 300 Hz
☐ Video bandwidth (VBW) settable to at least 3 kHz
☐ Peak-hold measurement mode
☐ Averaging (RMS) detection and/or trace averaging (with sample detection) measurement mode(s) (“max/min” averaging is not applicable under this item)
☐ Dynamic range sufficient to provide accurate measurement of signal under test with respect to AM IBOC mask
☐ Supports calibrated measurement with 300 Hz RBW, 3 kHz VBW, 200 kHz span

Hybrid FM IBOC mask compliance measurements (check off each item to certify compliance):

☐ Minimum frequency range: 85 MHz – 110 MHz
☐ Resolution bandwidth (RBW) settable to 1 kHz
☐ Video bandwidth (VBW) settable to at least 10 kHz
☐ Peak-hold measurement mode
☐ Averaging (RMS) detection and/or trace averaging (with sample detection) measurement mode(s) (“max/min” averaging is not applicable under this item)
☐ Dynamic range sufficient to provide accurate measurement of signal under test with respect to FM IBOC mask
☐ Supports calibrated measurement with 1 kHz RBW, 10 kHz VBW, 2 MHz span

By signing and submitting this form I certify that:

- I am authorized to make this submission on behalf of (company name) ______________________
- I understand that the inclusion of this equipment in Annex 2 of NRSC-G201 is at the sole discretion of the NRSC and that the NRSC may remove it from this list at any time.

SIGNATURE	DATE

ANNEX 4 – A Method for Measuring Hybrid FM IBOC Signals on Transmission Systems with Independent Digital and Analog Transmission Lines Using a CHIMP (Combined Hybrid IBOC Measurement Package)

A method for Measuring Hybrid FM IBOC Signals on Transmission Systems with Independent Analog and Digital Signal Transmission Lines

such as
Dual-Input-Antenna Systems and Separate–Antenna Systems

Utilizing a CHIMP
(Combined Hybrid IBOC Measurement Package)

Randy Mullinax
Senior Vice President Engineering
Clear Channel Radio

With Editorial Assistance by
David Maxson
Broadcast Signal Lab

September 2008

1. Introduction

This document demonstrates a method for verifying that a hybrid FM IBOC transmission system whose analog and digital components are maintained on separate transmission lines complies with the NRSC-5 standard's RF mask. The method includes the use of a purpose-built low-level signal combiner that simulates the broadcast combined hybrid FM IBOC signal. For convenience, combiner device has been given the name "CHIMP," which stands for Combined Hybrid IBOC Measurement Package.

When dual-input antennas or separate antennas are employed for transmitting the analog and digital components of the hybrid FM IBOC signal, special measurement procedures are necessary to demonstrate the compliance of a transmitted IBOC signal with the iBiquity HD Radio FM Transmission System Specifications (NRSC-5 Normative Reference Document 6, with further discussion in NRSC Guideline Document G-201). These transmission architectures have no common transmission line from which the combined digital and analog signals can be sampled before they reach their antenna(s). For this reason, this paper uses the term *separate line* to describe any IBOC system that maintains separate transmission lines for the analog and digital IBOC signals, such as dual-input antenna systems and separate antenna systems.

Since there is no point in a separate-line system where the combined hybrid IBOC signal can be sampled, additional steps must be taken to assess the hybrid signal, including establishing the analog reference level for measurement of the digital signal. Also, the combined emissions of the two transmission systems – digital and analog – may sum to exceed the RF mask, while each individual transmission appears compliant, particularly on certain third-order intermodulation frequencies where spectral regrowth may occur.

This measurement procedure does not determine the required digital transmitter power output. This value must be computed in advance based on the required digital ERP (20 dB below the analog ERP), the antenna gain, line loss and any other system losses. The required output power of the digital transmitter should be computed in advance and the digital transmitter should be operating at this power level before the measurements begin.

2. The Design of the CHIMP

Equipment List

To facilitate the measurements, the following equipment is required.

QTY.	DESCRIPTION
1	Spectrum Analyzer (Agilent E4402B or equivalent)
1	Splitter/Combiner (MiniCircuits ZFSC-2-2 or equivalent)
2	6 dB Attenuator Pads
1	Variable Attenuator or assortment of fixed pads
-	Coax Cables for hookup (double-shielded preferred)

In addition to the equipment listed above, there must be a directional coupler or other suitable directional RF sample available in both the analog and digital transmission lines to facilitate the measurements. An RF sample that is not directional will cause significant measurement error. Careful attention must be paid to the specifications of the directional couplers employed in the analog and digital transmission lines. Determine from calibration data what the errors are for each coupler at the expected power levels and transmitter frequencies.

Connect the test equipment as shown in Figure 1. Use a 6 dB attenuator pad at each input to the Splitter/Combiner (if the MiniCircuits ZFSC-2-2 is used, the “reject load” shown in Figure 1 is internal). The spectrum analyzer should be pre-configured as normal for hybrid FM IBOC measurements.

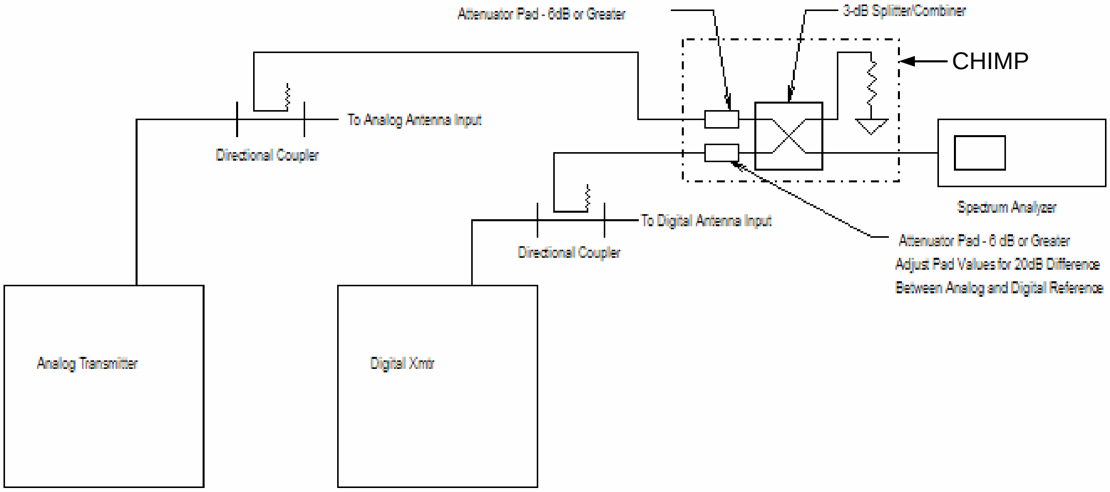


Figure 1
Combined Hybrid IBOC Measurement Package (“CHIMP”)
Sampling FM IBOC Signals from Separate Transmission Lines

3. CHIMP Operation

Typical Settings

Frequency – Center frequency of FM carrier
Span – 2.0 MHz
Detector – Sample
Data Points – Maximum
Resolution Bandwidth – 1 kHz
Video Bandwidth – ≥1 kHz
Sweep/Trace Averaging – ON – up to 100 sweeps
Averaging Detector Type – Pwr (also called RMS on some instruments)
Marker – Normal – Center frequency of FM carrier
Input power level to the spectrum analyzer mixer should be at no higher level than about 10 dB below the instrument's 1 dB compression point.

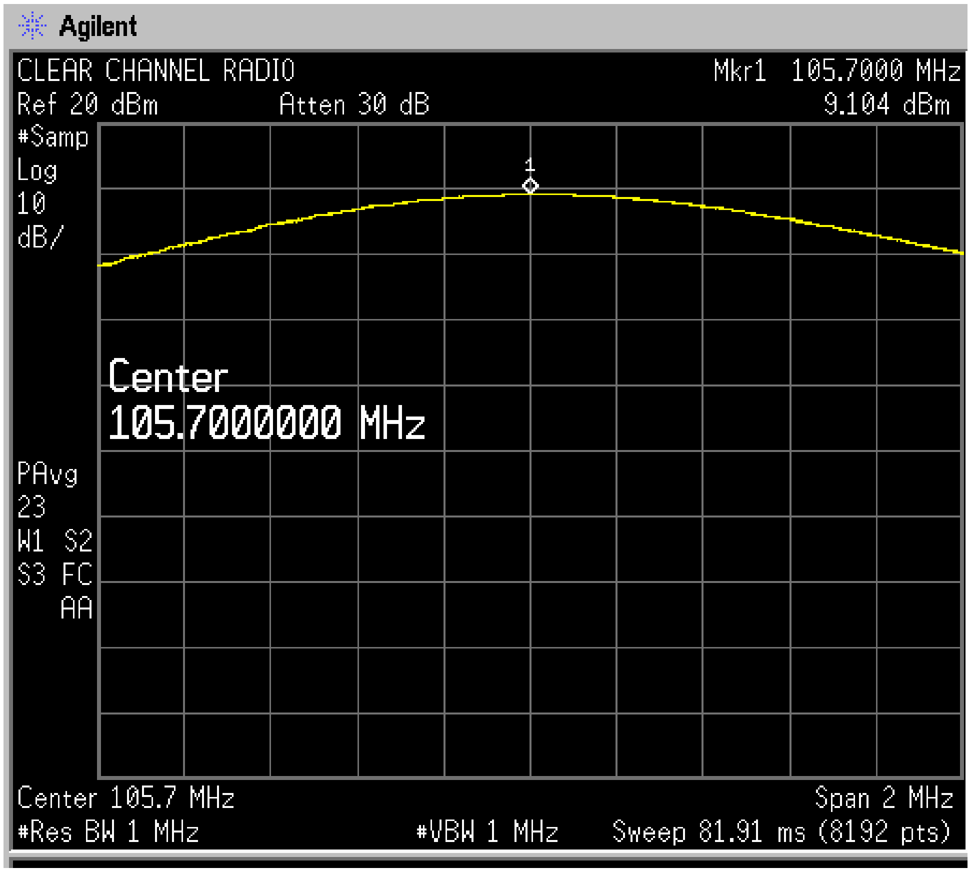
Maintain Stable Loads on Splitter/Combiner

The 6 dB pads should remain connected to the splitter/combiner at all times during the measurements to avoid significant errors. These pads provide the required isolation when one of the sample cables is removed to establish reference levels. The spectrum analyzer is assumed to have a precision 50 Ω input impedance, which is necessary to properly load the combiner unit.

Measurements illustrated in this paper were conducted using the equipment listed while monitoring the reference level with a short circuit, open circuit and 50 Ω load connected to the 6 dB attenuator pad on the opposite input of the splitter/combiner from that of the sample being measured. In all cases, the differences in the reference level were found to be less than 0.1 dB. The pads also reduce any errors associated with the reactive nature (poor source match) of the directional RF samples.

Initial Reference Levels

To establish the "analog reference level" (the basis is the level of the unmodulated analog carrier - Since it is often impractical to interrupt modulation, essentially the same result will be obtained by measuring the total power of the frequency modulated wave within its occupied bandwidth. Disconnect the digital RF sample cable from the 6 dB attenuator pad and leave the pad connected to the splitter/combiner. Change the Resolution Bandwidth and the Video Bandwidth of the spectrum analyzer to 1.0 MHz and restart averaging. Adjust the reference amplitude for an on-screen display. The display should be similar to Figure 2 (only about 10 sweeps are necessary to allow the analyzer to average the analog reference level).

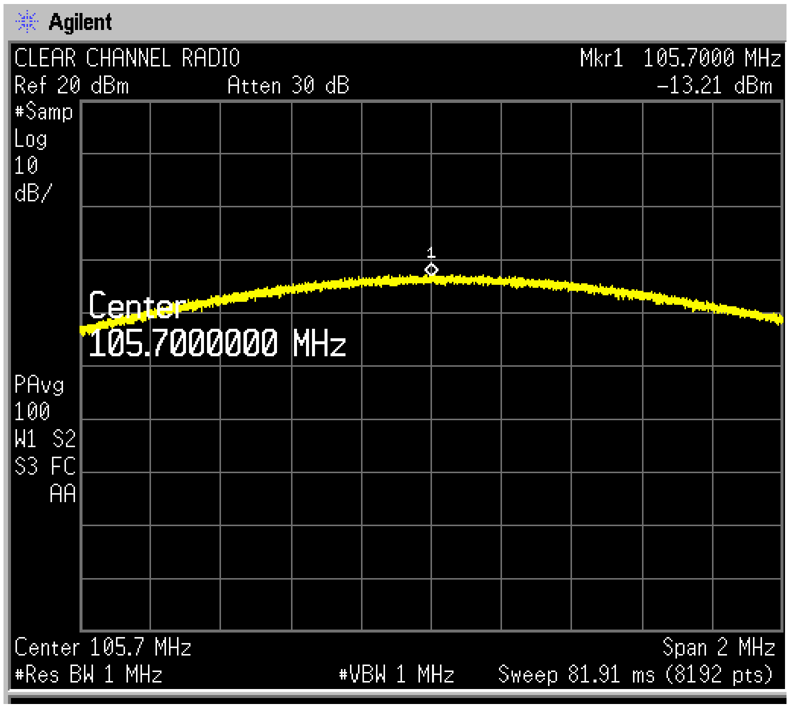


CLEAR CHANNEL RADIO
Mkr1 105.7000 MHz
Ref 20 dBm
Atten 30 dB
9.104 dBm
#Samp
Log
10
dB/
Center
105.7000000 MHz
PAvg
23
W1 S2
S3 FC
AA
Center 105.7 MHz
Span 2 MHz
#Res BW 1 MHz
#VBW 1 MHz
Sweep 81.91 ms (8192 pts)

Figure 2
Establishing Analog FM Reference Level
with Wide Resolution Bandwidth

Make a notation of the level indicated by the marker. In this example it is +9.1 dBm. Note that the 1.0 MHz Video Bandwidth will have very little effect on the analog reference level (less than 0.1 dB.

To establish the “digital reference level”, reconnect the digital RF sample cable and disconnect the analog RF sample cable from the 6 dB attenuator pad but again leave the pad connected to the splitter/combiner. Restart averaging and if necessary, adjust the reference amplitude for an on-screen display (restart averaging again if any adjustment to the reference amplitude is made). Allow the analyzer to average at least 50 sweeps. The display should appear similar to Figure 3.



CLEAR CHANNEL RADIO
Mkr1 105.7000 MHz
Ref 20 dBm
Atten 30 dB
-13.21 dBm
#Samp
Log
10
dB/
Center
105.7000000 MHz
PAvg
100
W1 S2
S3 FC
AA
Center 105.7 MHz
Span 2 MHz
#Res BW 1 MHz
#VBW 1 MHz
Sweep 81.91 ms (8192 pts)

Figure 3
Establishing IBOC Digital Reference Level
with Wide Resolution Bandwidth

Make a notation of the level indicated by the marker which in this example is -13.2 dBm.

Calculate Level Correction Required

From the RF levels noted above, calculate the amount of additional attenuation required so that the digital reference level will be as close to 20 dB as possible below the analog reference level. This assumes that the initial setup of the two transmission systems resulted in a digital ERP exactly 20 dB less than the analog ERP, as expected.

In this example, the initial analog reference level of approximately +9 dBm is 22 dB greater than the digital reference level of approximately -13 dBm. Thus, 2 dB of additional attenuation should be placed on the analog side of the splitter/combiner so that the digital reference level will be 20 dB below the analog reference level.

Determine whether additional corrections need to be added to adjust for differing coupler ratios, coupler calibration offsets, and sample line losses. Add (or subtract) the appropriate additional attenuation to the splitter/combiner device to obtain a correct 20 dB ratio between analog and digital signals.[1]

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[1] As a quick check, the attenuation required should be equal to the sum of line/filter/combiner losses and antenna gain (in dB) of the analog transmission system less the sum of the line/filter/combiner losses and antenna gain (in dB) of the digital transmission system. A positive result indicates the additional padding should be applied to the digital sample input to the CHIMP. A negative result requires the padding to be added to the analog sample input. This assumes that the two directional couplers employed have identical

Verify Level Correction

Insert the required attenuation calculated above, reconnect the analog RF sample cable and disconnect the digital RF sample cable. Restart averaging the then note the analog reference level. Adjust the reference amplitude so that it is equal to the level indicated by the marker as shown in Figure 4.

If desired, engage the “delta marker” function with the analog reference level at the top of the display. This marker can be employed to view the differences in level, in dBc, of any point on the trace. It avoids having to repeatedly subtract the reading on the trace from the reference level (both in dBm).

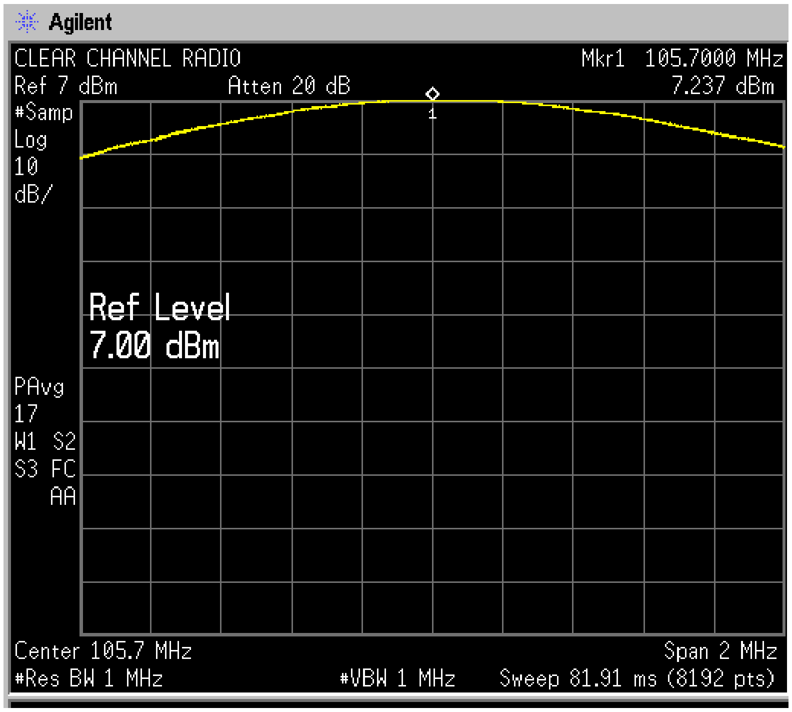

Figure 4
Analog FM Reference Level First Adjusted by Selection of CHIMP Input Attenuation Is then Set to the Top of the Display

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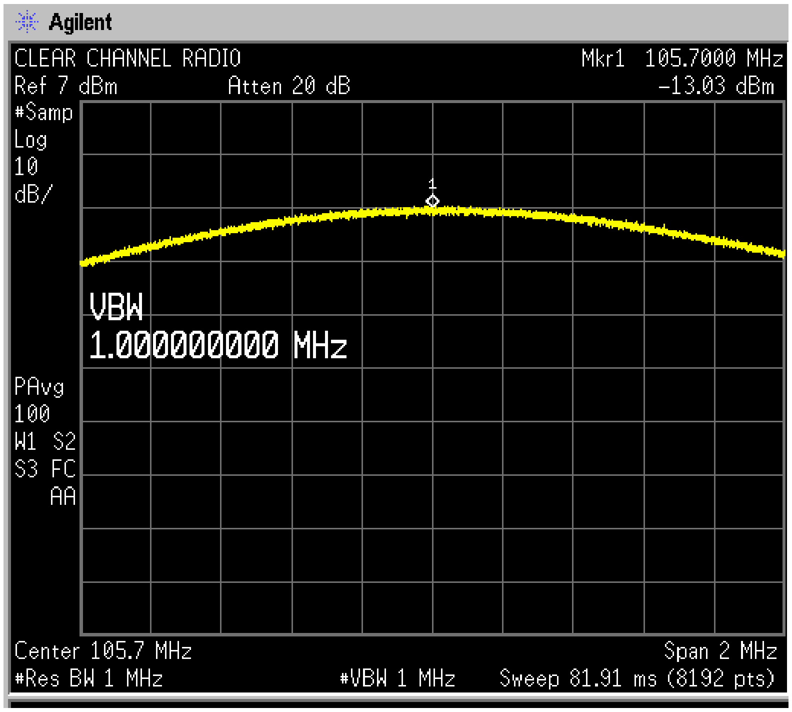
coupling ratios, that the sample cables have identical loss, and that sampling is done close to the transmitter outputs.



CLEAR CHANNEL RADIO
Mkr1 105.7000 MHz
Ref 7 dBm
Atten 20 dB
-13.03 dBm
#Samp
Log
10
dB/
VBW
1.000000000 MHz
PAvg
100
W1 S2
S3 FC
AA
Center 105.7 MHz
Span 2 MHz
#Res BW 1 MHz
#VBW 1 MHz
Sweep 81.91 ms (8192 pts)

Figure 5
Digital Reference Level Is Observed to Be Certain It Is At the Expected Level with Respect to the Top of the Display
(Typically -20 dBc, but may depend on actual system gains & losses as calculated)

Disconnect the analog RF sample cable and reconnect the digital RF sample cable (leaving the attenuator pads connected to the splitter/combiner as before), restart averaging and after 50 or more samples, verify that the digital reference level is 20 dB below the analog reference level as shown in Figure 5.

Perform Measurements

At this point, conventional hybrid FM IBOC measurements can begin by reconnecting the analog RF sample cable (both analog and digital sample cables should now be connected), change the Resolution Bandwidth to 1.0 kHz and the Video Bandwidth to 10 kHz or higher. Then restart the averaging to clear the memory of old display data. After 100 sweeps, the display should look similar to Figure 6.

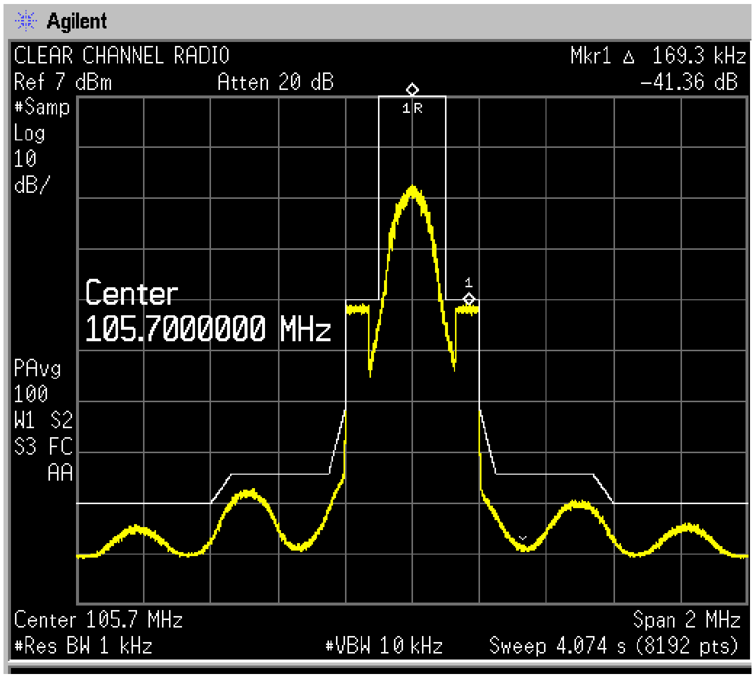


Figure 6
Resulting Combined Hybrid FM IBOC Signal Produced by the CHIMP and Measured by the Analyzer

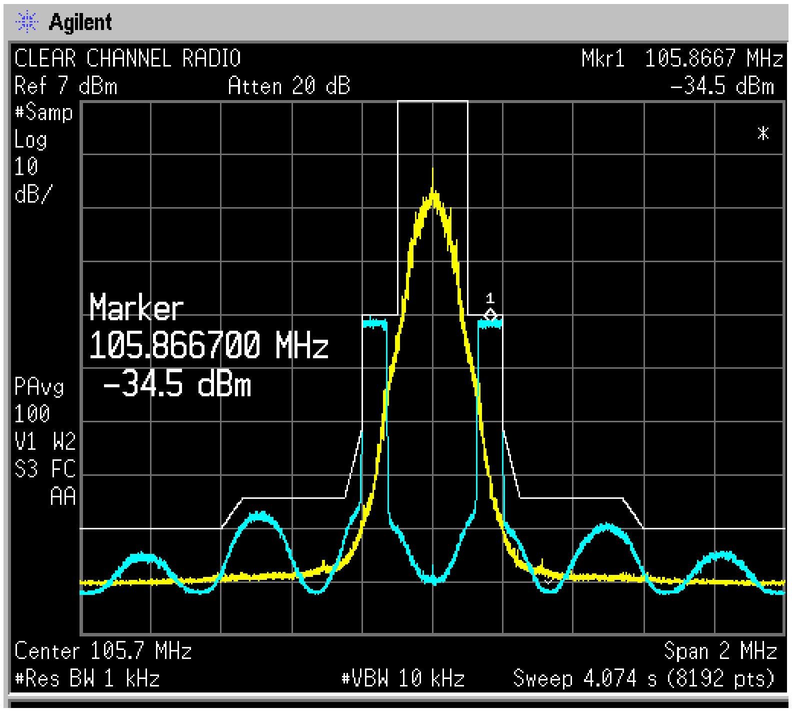


Figure 7
Analog and Digital Signals Sampled Independently through the CHIMP; Displayed as Two Traces

<u>Diagnostics</u>

In addition to the combined measurements, analog or digital-only measurements can be made by disconnecting one the RF sample cables. This can be very helpful in determining the cause of any out-of-compliance conditions. Figure 7 shows an overlay of the analog only and digital only signals. As can be seen, the "regrowth" products are almost entirely attributable to the digital transmitter as in this case, the digital transmitter does not utilize any form of "adaptive pre-correction". The facilities in this example consist of separate ½-wave spaced analog and digital antennas which are physically separated by approximately 40 feet. As a result, the isolation between the antennas is greater than 40 dB.

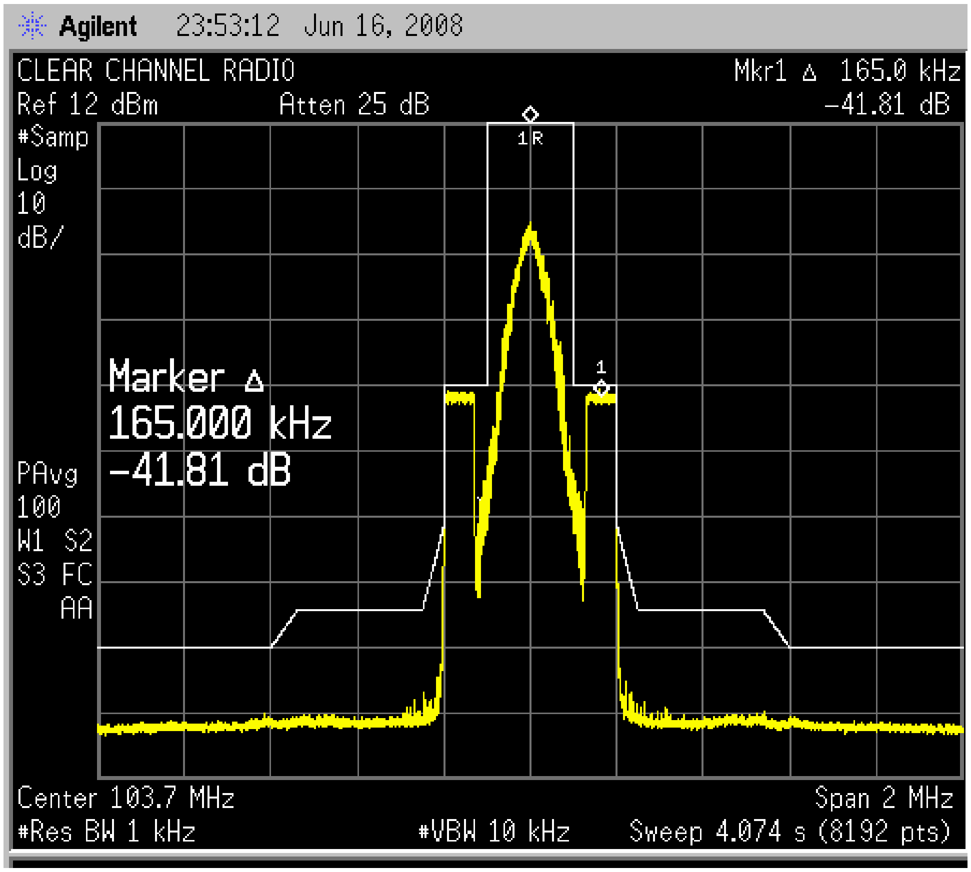


Figure 8
CHIMP-based Measurement of a Hybrid FM IBOC Station with Transmission Characteristics that Differ from the Station Represented by Figures 6 & 7

Figure 8 shows a more ideal hybrid IBOC display. In this example the facilities consist of interleaved analog and digital antennas with opposite circular polarization (the analog antenna is right-hand circular and the digital antenna is left-hand circular). Again, the isolation between the antennas is greater than 40 dB and in this case, the digital transmitter incorporates “adaptive pre-correction”.

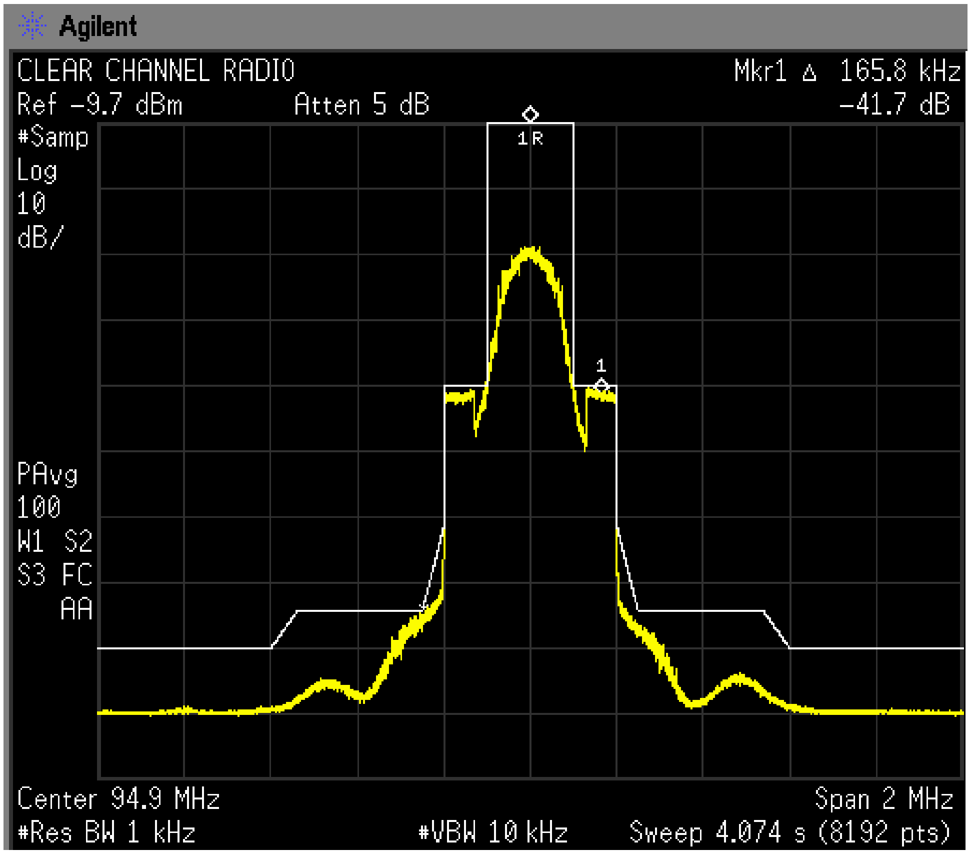


Figure 9
CHIMP-based Measurement of a Hybrid FM IBOC Station with Transmission Characteristics that Differ from the Stations Represented by Figures 6, 7 & 8

Figure 9 shows a less-than-ideal hybrid IBOC display. In this example the facilities consist of a dual-input antenna system where the analog to digital isolation is less than 25 dB. A ferrite isolator was installed in the digital transmission line to achieve an analog to digital isolation to approximately 50 dB. Again, in this example, the digital transmitter does not utilize any form of "adaptive pre-correction."

4. Conclusion

The Combined Hybrid IBOC Measurement Package ("CHIMP") as described in this paper is a reliable tool for evaluating the emissions of hybrid FM IBOC signals that are transmitted by systems with separate-line architectures. For the CHIMP to provide reliable results, the following conditions must be met:

- The transmitted power ratio between the analog and the digital components of the hybrid FM IBOC signal must be properly established with accurate transmitter power, line loss, and antenna gain information on both the analog and digital transmission chains,
- The RF sample from each transmission line must be directional (forward) with sufficient directivity to prevent measurement error from reverse path crosstalk,
- Proper isolation should be designed into the system to prevent measurement error from reverse path crosstalk (and to prevent unnecessary generation of intermodulation products within the output of each power amplifier),
- The CHIMP should contain suitable pads placed on the inputs to the CHIMP combiner to provide nearly constant impedance to the output of the CHIMP combiner to enable reliable measurements when one input has been disconnected.
- Variable attenuation at the CHIMP inputs should have sufficient precision to align the analog and digital power levels according to the calculated transmitted ratio.

Figures 2-7 – WWVA-FM, Canton, GA (Atlanta metro)
Figure 8 – WKZP Walden, TN (Chattanooga metro)
Figure 9 – WKSJ-FM, Mobile, AL

ANNEX 5 – Recommended AM antenna bandwidth characteristics

Recommended AM antenna bandwidth specifications

The recommended specifications in this annex are based on information from Rackley and Dawson in Reference [14], as presented by Maxson in Chapter 12 of Reference [4].

These specifications represent optimal performance objectives for hybrid AM IBOC antenna system design. Due to the challenges of antenna system design and implementation, it may not be practicable for some AM facilities to fully conform with these specifications. Systems not meeting these criteria have been shown to provide satisfactory hybrid AM IBOC service. The broadcaster should be aware that the quality and reliability of digital service may diminish as the antenna system performance deviates from these specifications.

Impedance Bandwidth

Shown in Table 1 are the suggested impedance bandwidth performance specifications for hybrid AM IBOC stations.

Table 1. Suggested Impedance Bandwidth Performance Specifications for Hybrid AM IBOC Stations

Frequency range with respect to reference channel center frequency (kHz)	Hybrid IBOC digital signal components	Desired performance
+15 to +10	● Primary subcarriers	VSWR below 1.40:1
-15 to -10		
−10 to −5	● Secondary subcarriers ● PIDS subcarriers	VSWR below 1.20:1
+10 to +5		
−5 to +5	● Tertiary subcarriers ● Analog sidebands ● Reference subcarriers	Hermitian Symmetry - *impedance at any frequency within 1.035:1 of the complex conjugate of the impedance at the mirror image frequency*

The most common method for measuring the impedance bandwidth of an AM antenna system is to disconnect the transmission line at the transmitter output and attach an impedance measuring instrument to the antenna system at this point. By attaching at this point, the instrument captures the complex impedances of transmission lines, phasing and tuning units, and the antenna elements themselves. However, in this case the instrument does not capture the impedance-changing effects of the transmitter's internal components, such as its matching network or its solid state combining network (if applicable).

It is anticipated that the transmitter manufacturer will supply the broadcaster with a correction figure or curve to apply to the results of the antenna system impedance bandwidth measurements. This correction figure or curve should be applied to the measurement result before making a comparison with the suggested performance specifications in Table 1.

Some contemporary models of AM transmitter incorporate internal impedance bandwidth-measuring circuitry that relies on true power analysis of the signal. Such devices make impedance bandwidth analysis more convenient and reliable because they make antenna system measurements without requiring the transmission line to be disconnected and automatically account for combiner and network characteristics internal to the transmitter. Because transmitter designs vary, consult the transmitter manual or the manufacturer for instructions on the best way to obtain a corrected impedance bandwidth measurement of a station's antenna system.

Rationale for Impedance Bandwidth Measurement Procedure

The ideal way to examine the antenna system characteristics is to view the transmission path from the "driving point" of the transmitter, as this is where the antenna system should be optimally matched to the source impedance of the amplifier's active components. This is desirable because any mismatch reflects to the amplifier and the consequence of this is distortion. By definition the driving point is situated at the output of the final amplifier ahead of any matching network.

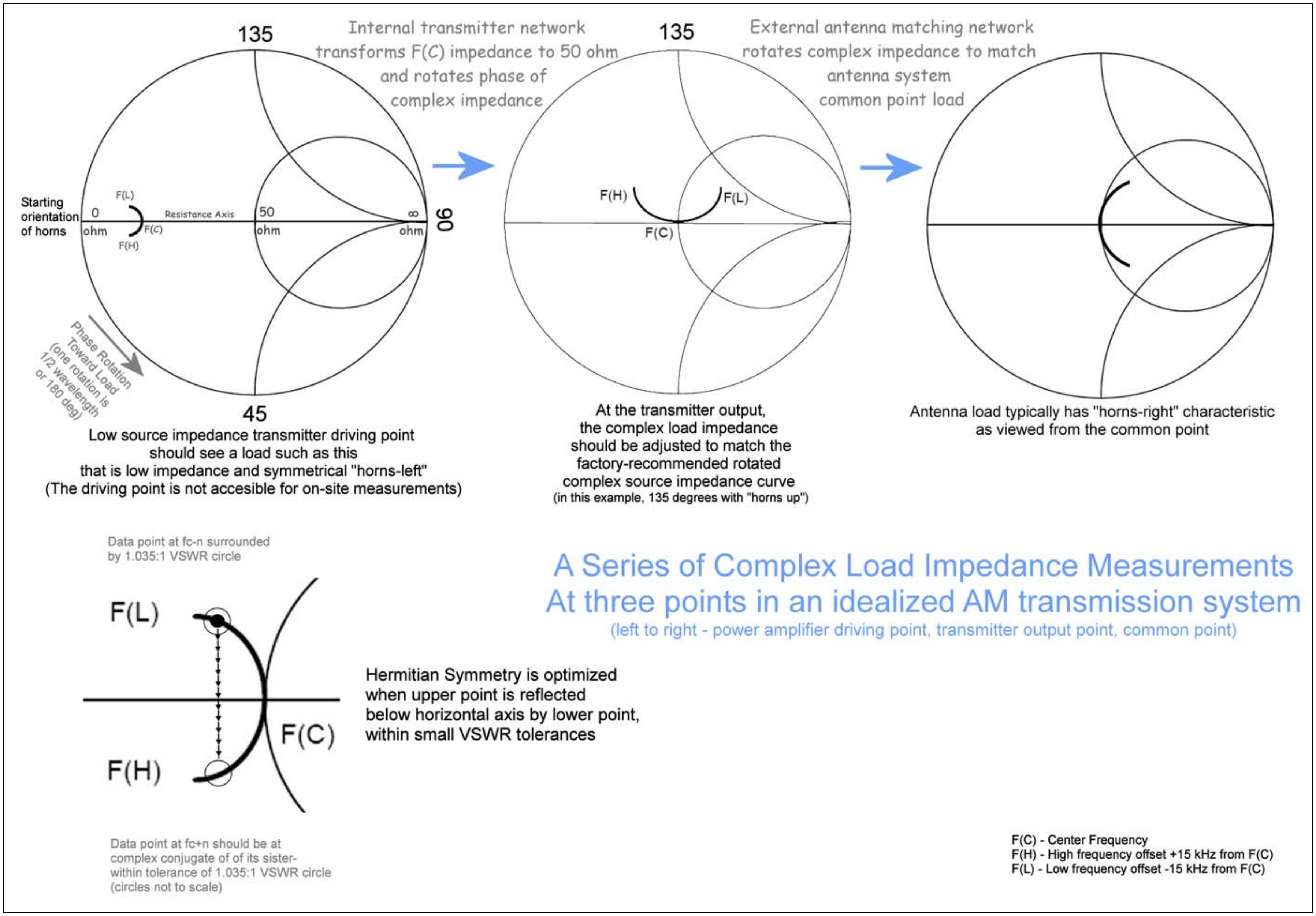
However, in today's solid-state transmitters, multiple amplifier modules are combined to produce a higher output level, such that numerous driving points are combined (with carefully tuned delays) to drive the output network. This point in the circuit is known as the "amplifier summing point." The summing point of multiple amplifiers has a source impedance that is typically not at the target value of 50 ohms (and often in the single digits). Consequently, the transmitter will often include an internal matching network and/or RF filtering (typically bandpass or lowpass) intended to transform the combined amplifier output to a nominal 50 ohm source impedance for driving the antenna system.

By disconnecting the transmission line at the transmitter output and connecting the impedance measuring device to the antenna system at that point, the measuring device will measure the net impedance of all antenna system components, excluding that of the (internal to the transmitter) matching network. This internal matching network introduces a phase rotation which is difficult to characterize since it is impractical to make an impedance measurement from the amplifier summing point to the matching network output using an external impedance measuring device, due to the non-standard impedance (at the matching point) and the difficulty in reliably accessing the matching point with a test connection. This is why it is necessary for the transmitter manufacturer to supply a correction figure or curve with the transmitter, to be applied to the results of the antenna system impedance bandwidth measurements.

The final antenna system impedance bandwidth measurements must have the phase rotation of the internal matching network subtracted from the external measurement to reveal what the amplifier "sees" at the driving point. It is this phase-corrected impedance measurement that must be evaluated for bandwidth flatness and Hermitian symmetry. For the most accurate results, it is recommended that the matching network corrections be presented not simply as a single phase rotation value, but instead as a curve of phase/amplitude response across the 30 kHz bandwidth of the transmitter centered on the station's frequency (or as a complex impedance plot, such as on a Smith Chart).

Hermitian Symmetry

Much has been written to explain Hermitian Symmetry, so this concept is not defined here. In simple terms, and assuming that the complex impedance-versus-frequency measurement has a curved shape, the tips of that curve (sometimes called "horns") would ideally appear on a Smith Chart with the horns pointing to the left (see Figure 1). In the horns-left condition the load is in the parallel resonant condition and a voltage source will deliver constant power independent of frequency. In the horns-right condition the load is in the series resonant condition and a current source will deliver constant power independent of frequency. Most AM transmitters are voltage sources and should operate better in a horns-left condition at the driving point.



Internal transmitter network transforms F(C) impedance to 50 ohm and rotates phase of complex impedance

External antenna matching network rotates complex impedance to match antenna system common point load

Low source impedance transmitter driving point should see a load such as this that is low impedance and symmetrical "horns-left" (The driving point is not accesible for on-site measurements)

At the transmitter output, the complex load impedance should be adjusted to match the factory-recommended rotated complex source impedance curve (in this example, 135 degrees with "horns up")

Antenna load typically has "horns-right" characteristic as viewed from the common point

Data point at fc-n surrounded by 1.035:1 VSWR circle

A Series of Complex Load Impedance Measurements At three points in an idealized AM transmission system

(left to right - power amplifier driving point, transmitter output point, common point)

Hermitian Symmetry is optimized when upper point is reflected below horizontal axis by lower point, within small VSWR tolerances

Data point at fc+n should be at complex conjugate of of its sister- within tolerance of 1.035:1 VSWR circle (circles not to scale)

F(C) - Center Frequency
F(H) - High frequency offset +15 kHz from F(C)
F(L) - Low frequency offset -15 kHz from F(C)

Figure 1. Example Smith Charts illustrating phase rotation and impedance transformation through an AM transmission system. Source: Maxson, derived from Figure 12.7 of [4]; based on Rackley, BEC proceedings, 2004 [16].

When adjusting a hybrid AM transmission system for Hermitian symmetry:

1) Determine whether the ideal symmetry for the transmitter is horns-left or horns-right (usually horns-left);

2) Obtain (from the manufacturer) the nominal phase rotation of the transmitter's internal combining and output networks;

3) Measure the impedance bandwidth of the AM transmission system from the transmitter output point;

4) Adjust the measured curve (obtained in step 3) by the transmitter's internal phase rotation values (from step 2) to obtain the impedance bandwidth at the driving point of the power amplifier;

5) Examine the adjusted measurement for its deviation from the specifications in Table 1;

6) Adjust the AM transmission system to obtain adjusted measurements that conform as closely as practicable to the specifications in Table 1.

Hybrid AM IBOC stations may perform adequately outside the Table 1 performance boundaries, if they do not deviate too far. The quality of the digital portion of the hybrid AM IBOC signal deteriorates with increased deviation from the optimal values presented in Table 1.

Broad symmetry across the entire channel is hard to achieve in many antenna system designs. The recommended symmetry across the ± 5 kHz analog spectrum is most critical because it is this symmetry that enables the upper and lower sidebands of the tertiary digital signals to self-cancel in the analog receiver. With good symmetry to ± 5 kHz, analog receivers experience minimal digital interference to the reception of the analog host.

The recommended ideal Hermitian symmetry value, 1.035:1, is not a VSWR *per se*, but the difference between a VSWR at one frequency offset from carrier and the VSWR at the opposite frequency offset from carrier. For example, if the VSWR at 5 kHz might be 1.2:1 on the upper sideband, this recommendation says the VSWR on the lower sideband should be between 1.165 and 1.235:1 in one dimension; in two dimensions it is a circle, whose radius is 1.035:1, around the target 1.2:1 VSWR point at 5 kHz on a Smith Chart.

It is also helpful to obtain reasonable symmetry on the secondary digital sidebands (5-10 kHz), but it is less important for minimizing analog reception noise due to the narrow bandpass of common analog receivers. In addition, good symmetry out to 10 kHz also promotes, in the IBOC receiver, joint decoding of the upper and lower secondary and tertiary sidebands and self-cancellation of the analog host signal for optimum digital detection.

Pattern Bandwidth

In addition to the impedance bandwidth issues discussed above, the role of pattern bandwidth in hybrid AM IBOC system design should be acknowledged. The pattern bandwidth of a directional AM station is the variation in the station's radiation pattern depending on the frequency and azimuth. Ideally, the pattern is identical for every frequency within the station's necessary bandwidth (±15 kHz for hybrid AM IBOC operation). In practice, the pattern bandwidth is relatively flat within the main lobe of the pattern, and may vary substantially at other azimuths. This is the reason that the NRSC-G201 Guideline recommends all directional hybrid AM IBOC mask measurements be conducted in the main lobe.

The work of Dawson and Rackley, among others, has resulted in a recommended pattern bandwidth performance for directional AM antenna systems.[1] Dawson and Rackley recommend that, "...throughout the major coverage areas of the pattern(s), amplitude response is within ± 2 dB and phase response is within 5 μs (or ±. In simple terms, assuming there is a curve to the impedance bandwidth-by-frequency measurement 27º) across the entire 30 kHz-wide passband." This performance is best evaluated by computer modeling of the antenna system. There is no established practice for performing field measurement of pattern bandwidth.

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[1] See, for example "So, What Have We Learned, or What to Do about IBOC," Stephen S, Lockwood, slides, May 26, 2005, Hatfield and Dawson, www.hatdaw.com.

ANNEX 6 – AM Transmitter Modulation Technical Primer for NRSC Measurement Guideline

AM Transmitter Modulation Technical Primer for NRSC Measurement Guideline

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A general, band limited, RF signal may be represented as follows:

$$s(t) = i(t)\cos(\omega_c t) - q(t)\sin(\omega_c t) \quad Eq.1$$

In *Eq*.1, *i(t)* and *q(t)* constitute the *complex envelope* in Cartesian form. They are sometimes referred to as the *quadrature components* or I and Q for short. For RF signals where the upper and lower sidebands are symmetrical, such as AM, one of the components may be considered to be zero. It is important to note that each of the quadrature components generally has bandwidth equal to that of the RF signal, *s(t)*. There is also a direct linear relationship between the spectra of the baseband complex envelope and the passband RF such that a linear filter applied to the complex envelope centered at zero frequency will have the same effect on the passband, centered at the carrier frequency, ω_c. For these reasons the quadrature components are often used to represent the radio signal in a baseband signal processing system.

Another mathematical representation is the polar form:

$$s(t) = r(t)\cos(\omega_c t + \varphi(t)) \quad Eq.2$$

where:

$$r(t) = \sqrt{i^2(t) + q^2(t)} \quad Eq.3$$

$$\varphi(t) = \tan^{-1}\left(\frac{q(t)}{i(t)}\right) \quad Eq.4$$

In the polar representation, *r(t)* is the envelope and *φ(t)* is the phase.

The polar representation is important for AM broadcasting because virtually all modern AM broadcast transmitters operate using envelope elimination and restoration (EER) also known as the Kahn technique. All EER transmitters share an important aspect that the audio frequency envelope (<100 kHz) and the radio frequency phase signal are multiplied together in the final amplifier stage as shown in *Eq. 2*. Many transmitters use pulse duration modulation (PDM) to generate the audio frequency envelope and apply it as a variable power supply voltage (modulator) to the final amplifier stage. Other techniques including digital synthesis of the RF envelope (example – Harris DX series) may be used to accomplish envelope modulation but the end result is similar.

The EER approach benefits AM transmitters principally by allowing them to be smaller and operate at significantly higher efficiencies than the linear amplifiers (classes A, B and A/B) generally used for FM IBOC and TV broadcast transmitters.

Transmitters using EER may suffer from several types of non-linearities, including AM to AM, AM to PM, and differential time delay distortion between the envelope and RF phase channels, which increase the out-of-band emissions if not carefully corrected for. This is because the two component signals, the AF envelope and RF phase, have a highly non-linear relationship with the linear I and Q components as shown by *Eq. 3* and *Eq. 4.* These signals have considerably greater bandwidth than the broadcast signal *s(t)* and any misalignment between them when combined in the final amplifier will result in distortion and increased out-of-band emissions.

To be more specific, any difference of absolute time, non-flat frequency response or non-flat group delay as well as distortion in either of these signals will result in distortion of the output signal. This is unlike a linear amplification process where frequency response and group delay errors do not result in distortion. It is important to note that superposition does not apply in EER amplification because it is a nonlinear process. The sum of the spectra of the separately transmitted IBOC and AM signal components is not necessarily the same as the spectrum of the IBOC and AM signal components transmitted together. Consequently, measurements of occupied bandwidth for just one part of the signal (such as analog only), while useful, cannot be expected to hold when another part of the total signal is "added."

Many AM IBOC transmitters require a “mag - phase delay” adjustment which corrects for differences in the overall time delay between the audio frequency envelope and RF phase terms. The difference in time delay may be introduced, for example, in some PDM-type transmitters by interaction of the modulator lowpass filter with the varying impedance of different antenna systems. If this is not correctly adjusted, out-of-band emissions will be increased. However, this adjustment does not correct for differences in time as a function of frequency (i.e. non-flat group delay). It is also important to note:

- A linear (non-flat) frequency response in the envelope or phase channels will cause distortion (non-linear) of the final RF term. This will increase the occupied bandwidth and may violate the spectrum mask. This problem can be attributed to the non-linear relationship between the RF signal and the envelope and phase signal components;
- The envelope and phase bandwidths are much larger than required by analog-only AM modulation. For IBOC operation, simulations have shown that an envelope bandwidth of 45 to 60 kHz is required. This behavior may also be attributed to the non-linear relationship between the RF signal and the envelope and phase signal components.

Figure 1 shows an ideal power spectrum of the magnitude term of the hybrid AM IBOC signal (both digital and analog components present). Note that the envelope signal crosses -80 dBc at 65 kHz. This is a good indication of required envelope bandwidth.

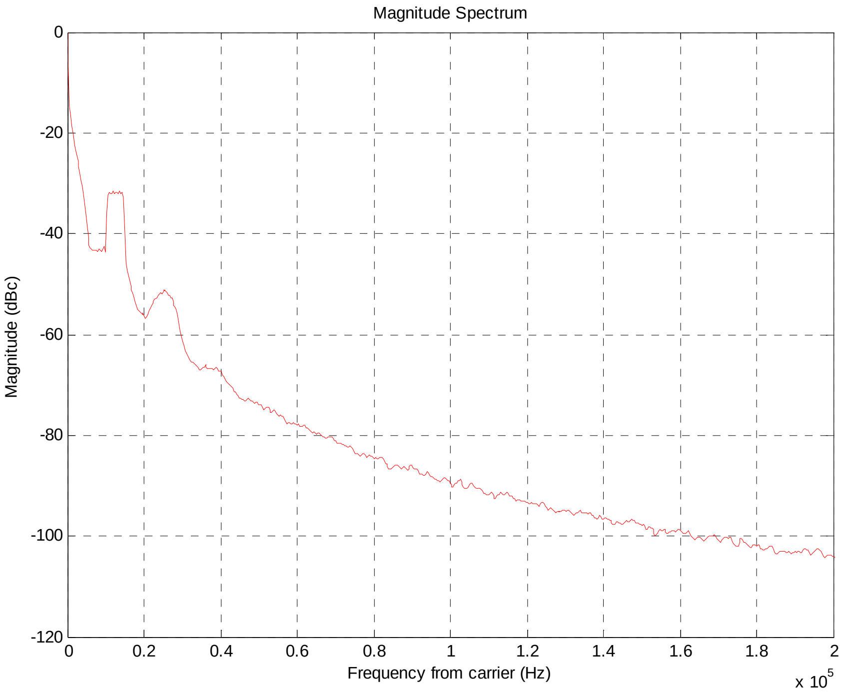

Figure 1. Envelope spectrum of hybrid AM IBOC

AM Audio / IBOC Interaction

It is also useful to consider the time domain behavior of the magnitude and phase signals by referring to *Eq. 3* and *Eq. 4.* The magnitude term is relatively free of discontinuities in time as it is simply the magnitude of the sum of the I and Q vectors. However the phase signal is not always so well-behaved.

The phase signal is defined by the arctangent of the quotient of I and Q. When I and Q are both very small, i.e. the magnitude is near zero, a small change in I or Q may make a large change in phase. Essentially, the smaller the magnitude of the signal, the higher the rate-of-change of phase, including nearly instantaneous phase reversals which dramatically increase the short-term bandwidth of the RF phase signal. Meanwhile, the envelope channel does not have enough modulation bandwidth to accurately track with the phase channel.

As a result, non linear products resulting in out-of-band emissions from the transmitter tend to be highest when the magnitude of the signal is small. For this reason, the envelope modulation bandwidth and linearity of the transmitter is particularly important near the 100% negative modulation point where carrier pinch-off would occur.

The signal being transmitted is the sum of the IBOC OFDM signal, the AM sidebands and the AM carrier. The out-of-band emissions are most likely to be large when the analog AM modulation is in the “trough.” To reduce out-of-band emissions on hybrid AM IBOC transmitters, it is generally recommended to ensure that the negative analog AM modulation depth is limited to 90% or less. Out-of-band emissions from the transmitter may tend to have bursts associated with these modulation troughs.

NRSC-G201

NRSC Document Improvement Proposal

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