NRSC REPORT

NATIONAL RADIO SYSTEMS COMMITTEE

NRSC-R203
Evaluation of the iBiquity Digital Corporation IBOC System – Part 1 – FM IBOC
November 29, 2001

Part I - Report

NAB: 1771 N Street, N.W.
Washington, DC 20036
Tel: (202) 429-5356 Fax: (202) 775-4981

CEA: 1919 South Eads Street
Arlington, VA 22202
Tel: (703) 907-7660 Fax: (703) 907-8113

Co-sponsored by the Consumer Electronics Association and the National Association of Broadcasters
http://www.nrscstandards.org

NOTICE

Published by
CONSUMER ELECTRONICS ASSOCIATION
Technology & Standards Department
1919 S. Eads St.
Arlington, VA 22202

NATIONAL ASSOCIATION OF BROADCASTERS
Science and Technology Department
1771 N Street, NW
Washington, DC 20036

FOREWORD

NRSC-R203, Evaluation of the iBiquity Digital Corporation IBOC System – Part 1 – FM IBOC, documents the NRSC's evaluation of the FM IBOC system which was subsequently selected by the FCC in October 2002 as the technology that will permit FM radio broadcasters to introduce digital operations. The DAB Subcommittee chairman at the time of adoption of NRSC-R203 was Milford Smith; the NRSC chairman at the time of adoption was Charles Morgan.

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.

Consumer Electronics Association
A sector of EIA

2500 Wilson Boulevard
Arlington, VA 22201-3834
(703) 907-7660
FAX (703) 907-7601

N A T I O N A L R A D I O S Y S T E M S C O M M I T T E E

National Association of Broadcasters

1771 N Street, NW
Washington, DC 20036-2800
(202) 429-5346
FAX (202) 775-4981

D A B S u b c o m m i t t e e

EVALUATION OF THE IBIQUITY DIGITAL CORPORATION IBOC SYSTEM

Part 1 – FM IBOC

Report from the
Evaluation Working Group
Dr. H. Donald Messer, Chairman

(as adopted by the Subcommittee on November 29, 2001)

Sponsored by the Consumer Electronics Association and the National Association of Broadcasters

Table of Contents

List of tables

List of figures

1 INTRODUCTION

This report on the performance and compatibility of the iBiquity Digital Corporation's FM in-band/on-channel (IBOC) digital radio system has been developed by the Evaluation Working Group (EWG, Table 1), Dr. H. Donald Messer, Chairman, of the National Radio Systems Committee's (NRSC's) Digital Audio Broadcasting (DAB) Subcommittee.

Table 1. Evaluation Working Group (EWG) participants†

ORGANIZATION	REPRESENTATIVE
Advanced Television Technology Center	Dr. Charles W. Einolf, Jr., Deputy Executive Director Sean C. Wallace, Systems Engineer
Broadcast Signal Lab	David Maxson
Consumer Electronics Association	Dave Wilson, Director, Engineering
CUE Corporation	Tom Schaffnit, consultant
Denny & Associates	Alan Rosner
Dolby Laboratories	Tim Carroll
Greater Media, Inc.	Milford K. Smith, Vice President, Engineering
iBiquity Digital Corporation	Glynn Walden, Vice President Broadcast Engineering Albert Shuldiner, Esq., Vice President and General Counsel Greg Nease Dr. Ellyn Sheffield
International Association of Audio Information Services (IAAIS)	Dave Andrews, Chief Technology Officer
International Broadcasting Bureau	Dr. H. Donald Messer, Chief, Spectrum Management (Chairman)
Jefferson-Pilot Communications	Tom Giglio, Vice President, Engineering
Journal Broadcast Group	Andy Laird, Vice President, Radio Engineering
National Association of Broadcasters	John Marino, Vice President, Science & Technology David Layer, Director, Advanced Engineering (Secretary)
National Public Radio	Jan Andrews, Senior Engineer
Susquehanna Radio Co.	Charles Morgan, Sr. Vice President
T. Keller Corporation	Tom Keller

† *Additional organizations participated on a less-frequent basis including ABC, Digital Radio Express, Sony, and Wye Consulting*

This work was done in pursuit of the DAB Subcommittee's Goals and Objectives, included in this report as Appendix A. The purpose of this NRSC IBOC evaluation is to determine if the iBiquity FM IBOC system is a significant improvement over the analog systems currently in use, and, to confirm that the impact of the IBOC digital sidebands on existing analog signals is both minimal and acceptable. Note that this report is not itself a standard for IBOC digital radio.

The evaluation effort culminating in this report is the latest in a series of similar evaluations done by the Subcommittee, starting in the 1995-96 timeframe (in conjunction with EIA/CEG, now CEA) on "first generation" IBOC systems,[1] then in 2000 when a "phase 1" evaluation of "next generation" IBOC systems was conducted.[2] This current evaluation effort is the most comprehensive one yet, and is the first

---

[1] The 1995-96 DAB evaluation with EIA was conducted on four different types of DAB systems—terrestrial new-band (specifically, the Eureka-147 system), satellite (the VOA-JPL S-band system), terrestrial in-band/adjacent channel (IBAC), and terrestrial IBOC (both FM and AM). A detailed report on the test results was published by EIA - see "Consumer Electronics Group, Electronic Industries Association, Digital Audio Radio Laboratory Tests - Transmission Quality Failure Characterization and Analog Compatibility," August 11, 1995.

[2] The NRSC's "phase 1" IBOC evaluation was based on preliminary performance data submitted by Lucent Digital Radio (LDR) and USA Digital Radio (USADR); detailed reports on the results of these evaluations were published by the NRSC – see "DAB

to be based on a full set of FM IBOC system laboratory and field test data collected in strict accordance with NRSC-developed test procedures.

Preparatory work on this report began well in advance of the receipt of test data to be analyzed. The EWG first convened in its present form (and under its present leadership) in March 1999, and met 10 times that year to develop evaluation criteria upon which to judge candidate IBOC DAB systems, as well as an Evaluation Guidelines document[3] which outlined the process by which the EWG would evaluate the data submissions expected from LDR and USADR in December of that year (the so-called "phase 1" evaluation).[4] In the first three months of 2000, the EWG met another 10 times, resulting in the release of two evaluation reports, one each on the LDR and USADR systems.[5]

The NRSC's focus then shifted to development of test procedures for the next phase of the evaluation, resulting in the development of FM and AM IBOC test procedures by the DAB Subcommittee's Test Procedures Working Group (TPWG).[6] The EWG re-convened on May 8, 2001 to begin preparing for receipt of data on iBiquity's FM IBOC system. Between May and August the group reviewed and refined its evaluation criteria based both on the experience gained from the phase 1 evaluation as well as on operational details of the iBiquity FM IBOC technology (*e.g.*, its "blend to analog" feature). Data evaluation began when, on August 8, 2001, a test data report prepared by iBiquity, the Advanced Television Technology Center (ATTC), and Dynastat was delivered to the NRSC ("FM IBOC Test Data Report").[7]

The information contained in the data report was collected by either iBiquity or ATTC in the presence of one or more NRSC observers (Table 2, retained by NAB and CEA), broadcast consulting engineers familiar with both the NRSC's FM IBOC test procedures as well as the underlying technologies and measurement techniques. Subjective evaluations performed on portions of this data were conducted by Dynastat and are documented in the data report, as well. The NRSC observers ensured that the tests were being conducted according to the NRSC's procedures, that the data being recorded (and ultimately submitted to the NRSC) was in fact the data being obtained, and in addition because of their expertise were able to help resolve testing issues as they arose, often in consultation with NAB and CEA staff and the DAB Subcommittee's Test Program Steering Committee.

Table 2. NRSC observers

ORGANIZATION	REPRESENTATIVE(S)	TASKS
Denny & Associates	Alan Rosner, P.E.	Principal field test observer – east coast and midwest
T. Keller Corporation	Tom Keller, President	Principal lab test observer Observer on FM field compatibility tests
Hammett & Edison	Stan Salek, P.E.	Principal field test observer – west coast

All of the conclusions and recommendations which follow in this evaluation report are based upon the information contained in the FM IBOC Test Data Report (including the SCA Test Report), upon information provided to the EWG from the NRSC observers, and upon subsequent analysis of this information. By and large, compatibility with existing analog services and the coverage afforded the new,

Subcommittee – Evaluation of Lucent Digital Radio's Submission to the NRSC DAB Subcommittee of Selected Laboratory and Field Test Results," April 8, 2000, and "DAB Subcommittee – Evaluation of USA Digital Radio's Submission to the NRSC DAB Subcommittee of Selected Laboratory and Field Test Results," April 8, 2000.

[3] See "DAB Subcommittee – In-band/on-channel (IBOC) Digital Audio Broadcasting (DAB) System Evaluation Guidelines," May 25, 1999 (published by the NRSC).

[4] USADR submitted a test report to the NRSC on December 15, 1999; LDR's submission was received on January 24, 2000.

[5] See footnote 2.

[6] The FM IBOC test procedures are included with this report as Appendices B and C.

[7] See Appendix L for a table of contents of this data report. Additional data, on SCA compatibility tests, was submitted to the NRSC by iBiquity and the ATTC on October 19, 2001 (a table of contents for the SCA test report is also included in Appendix L).

digital service were deemed of greater importance to the EWG than were some of the other aspects of IBOC system evaluation such as amount of auxiliary data capacity. This evaluation report is solely a technical evaluation and does not address costs of transition nor the costs of receiver implementation.

1.1 Test parameters

Detailed laboratory and field test procedures were developed by the DAB Subcommittee and are included with this report as Appendices B and C, respectively (these are discussed in greater detail in Section 3). These tests were conducted on the "baseline" iBiquity FM IBOC system (Table 3), commonly referred to as the "hybrid" mode of operation, generally recognized to be more technically challenging to implement than is the all-digital mode.[8] In addition, the hybrid mode represents the first step in the transition from analog to digital radio broadcasting and as such there is an immediate need to characterize its behavior.

Table 3. iBiquity FM IBOC system – baseline parameters

PARAMETER	VALUE
Main channel digital audio bit rate	96 kbps
IBOC digital sideband bandwidth (per side)	69 kHz (service mode MP1)[9]
IBOC digital sideband power level (total, with respect to total analog power level)	-20 dB
Auxiliary data rate	3-4 kbps (1 kbps dedicated; 2-3 kbps opportunistic)

1.2 Future work

There are two important IBOC-related tasks still facing the NRSC. Most immediately, an evaluation of iBiquity's AM IBOC system needs to be undertaken; this will commence as soon as the AM IBOC test data is released to the NRSC (this data is expected in December 2001), and will be reported as Part 2 of this report.

All of the test results analyzed in this report were obtained on a version of the iBiquity FM IBOC system implemented with MPEG-2 AAC perceptual audio coding. Since iBiquity has stated it intends to release its system commercially with their own proprietary audio coding technology (based on PAC, developed by Lucent Technologies), they have agreed to provide the NRSC with data on a system based on their own proprietary audio coding technology when available.

[8] See IBOC FM Test Data Report, Appendix A, for information on the various modes of operation.
[9] See IBOC FM Test Data Report, Appendix A, pg. 19, for a precise spectral occupancy description of this service mode.

2 CONCLUSIONS and RECOMMENDATIONS

Based on careful evaluation of the test data, the NRSC has concluded that the performance of the iBiquity FM IBOC system as tested represents a significant improvement over today's existing analog services. The impact of IBOC digital sidebands on the performance of existing main channel audio services is varied: listeners should not perceive an impact on the analog host signal, nor on the analog signals on carriers that are either co-channel or 2nd-adjacent channel with respect to an IBOC signal. With respect to carriers that are located 1st-adjacent to an IBOC signal, listeners within the protected contour should not perceive an impact, but a limited number of listeners may perceive an impact outside of the protected contour under certain conditions.

So, after nearly a decade of encouraging the development of IBOC DAB and now culminating with the formulation and execution of a comprehensive test program, the NRSC believes that the iBiquity FM IBOC system as tested will offer FM broadcasters significantly enhanced performance over that which is presently available from traditional analog FM broadcasting. The enhancements include almost full immunity from typical FM multipath reception problems, significantly improved full-stereo coverage, flexible data casting opportunities, and an efficient means for FM broadcasters to begin the transition to digital broadcasting.

The NRSC also believes that the tradeoffs necessary for the adoption of FM IBOC are relatively minor. With respect to the main channel audio signal, evaluation of test data shows that a small decrease in audio signal-to-noise ratio will be evident to some listeners in localized areas where 1st-adjacent stations, operating with the FM IBOC system, overlap the coverage of a desired station. However, listeners in these particular areas may also be subject to adjacent-channel *analog* interference which will tend to mask the IBOC-related interference, most appropriately characterized as band-limited "white" noise, rendering it inaudible under normal listening conditions. Also, all present-day mobile receivers include a stereo blend-to-mono function dynamically active under conditions of varying signal strength and adjacent channel interference. This characteristic of mobile receivers will also tend to mask any IBOC-related noise. The validity and effectiveness of these masking mechanisms is apparent from the rigorous subjective evaluations performed on the data obtained during the NRSC's adjacent-channel testing.

Extensive laboratory and field tests supervised by the NRSC and performed on this IBOC system show the feasibility of the iBiquity technology. Furthermore, the system as tested by the NRSC provides an extremely smooth and acceptable transition from digital to analog in areas of weak signal strength, offering broadcasters robust digital coverage for a new generation of digital receivers with no significant loss in existing analog coverage areas.

The NRSC therefore recommends that the iBiquity FM IBOC system as tested by the NRSC should be authorized by the FCC as an enhancement to FM broadcasting in the U.S., charting the course for an efficient transition to digital broadcasting with minimal impact on existing analog FM reception and no new spectrum requirements.

2.1 Digital performance

Given here are the NRSC's findings for each of the eight digital performance evaluation criteria. Each of these findings is elaborated on in Section 4 below:

Audio quality

The iBiquity hybrid FM IBOC system with MPEG-2 AAC perceptual audio coding demonstrates significantly improved audio quality compared to existing analog FM in mobile listening environments. Since the final version of this system will utilize a proprietary iBiquity perceptual audio coding algorithm and not MPEG-2 AAC, no direct findings on the unimpaired audio quality of the final system can be made at this time.

Service area

NRSC test results indicate that hybrid FM IBOC digital coverage is comparable to analog coverage along radial and loop routes tested. Due to FM IBOC's improved resistance to various types of interference (co- and adjacent channel, impulse noise, and multipath fading in particular), FM IBOC service may be obtained in areas where analog service is currently of unacceptable quality due to such interference.

Durability

NRSC test results demonstrate that the iBiquity hybrid FM IBOC system, compared to analog FM, is substantially more robust to impulse noise, co- and adjacent channel interference, and multipath fading.

Acquisition performance

The acquisition performance of the iBiquity hybrid FM IBOC system is identical to that of an analog FM radio since, by design, an IBOC receiver initially acquires using the analog portion of the hybrid FM IBOC signal.

Auxiliary data capacity

The iBiquity hybrid FM IBOC system design incorporates an auxiliary data transmission feature with a minimum capacity of 3-4 kbps. This system feature was not tested by the NRSC.

Behavior as signal degrades

NRSC testing has demonstrated that the iBiquity prototype hybrid FM IBOC receiver's audio during the blend process is perceived to have the same quality as does the analog audio, and, that the blend process itself does not degrade the IBOC receiver's audio quality below that of analog.

Stereo separation

FM IBOC receivers are expected to exhibit superior stereo separation compared to analog automotive FM receivers due to the fact that the FM IBOC receiver should be receiving digital stereo audio under circumstances for which an analog automotive FM receiver would be blending to mono.

Flexibility

There are a significant number of features in the iBiquity FM IBOC system which should provide for system flexibility and should offer broadcasters and receiver manufacturers opportunities to customize services and equipment for their particular goals, and offer the possibility of performance improvements in the future. None of these features were tested by the NRSC.

2.2 Analog compatibility

Given here are the NRSC's findings for both of the compatibility evaluation criteria. Each of these findings is elaborated on in Section 4 below:

Host analog signal impact

NRSC tests indicate that listeners should not perceive an impact on analog host reception due to hybrid FM IBOC operation.

Non-host analog signal impact

For the three cases considered, the following findings apply regarding the introduction of hybrid FM IBOC into the FM band:

Co-channel interference: no impact on analog reception (by design).

1st-adjacent channel interference: listeners within the protected contour should not perceive an impact, but a limited number of listeners may perceive an impact outside of the protected contour under certain conditions.

2nd-adjacent channel interference: NRSC tests indicated that some receivers (with performance similar to the NRSC analog automotive and portable receivers) should not experience an impact on performance due to 2nd-adjacent channel hybrid FM IBOC interference, however, a very limited number of receivers (with performance similar to the home hi-fi receiver used in the NRSC tests) might experience a negative impact for -30 to -40 dB (and more negative) D/U ratios.

Impact on SCA reception

Careful evaluation of test data shows that the digital SCA services tested (RDS and DARC) should not be adversely impacted by IBOC. For the case of analog SCA services, some questions still remain as to the impact of IBOC on such services. In order to answer these questions and to provide additional clarity to this matter, iBiquity, National Public Radio and the International Association of Audio Information Services have agreed to expeditiously perform a series of additional tests for the purpose of determining how certain SCA receivers will perform after IBOC is implemented on host and adjacent channel stations. The NRSC encourages the rapid completion of these tests in time to provide meaningful input to the FCC for its consideration.

2.3 "Baseline" mode of operation

The NRSC has only studied operation of this system using the baseline parameters (Table 3 above). The conclusions and recommendations in this report apply to that mode of operation only.

3 NRSC TEST PROGRAM

In this section, background information on the NRSC's FM IBOC test program is provided, including some of the basic attributes of the iBiquity FM IBOC system which were taken into account as the NRSC test procedures (Appendices B and C to this report) were developed.

To evaluate an IBOC radio system, two basic types of tests are required (done in both the laboratory and the field), both of which are found in the NRSC's IBOC test procedures:

- Performance tests: in the context of the NRSC's test procedures and evaluation reports, "performance tests" (sometimes called "digital performance tests") are those used to establish the performance of the IBOC digital radio system itself. Performance test results are obtained using an IBOC receiver or through direct observation of the received signal.
- Compatibility tests: again, in the context of the NRSC's IBOC evaluation, "compatibility tests" (sometimes referred to as "analog compatibility tests") are designed to determine the effect that the IBOC digital radio signal has on existing analog signals (main channel audio and subcarriers). Compatibility testing involves observing performance with IBOC digital sidebands alternately turned on and off; test results are obtained using either analog FM receivers or FM subcarrier receivers (analog or digital) or through direct observation of the received signal.

For each of these, two basic types of measurements are made:

- Objective measurements: where a parameter such as signal power, signal to noise ratio, or error rate is measured, typically by using test equipment designed specifically for that particular measurement (*e.g.*, power meter, error rate test set).
- Subjective measurements: involve human interpretation or opinion – not something that can be simply measured with a device. In the NRSC test program, subjective measurements involve determining the quality of audio recordings by having people listen to them and rate them according to a pre-defined quality scale.

Subjective evaluation is especially important when trying to assess the quality of IBOC digital audio since the IBOC radio system relies upon perceptual audio coding for audio transmission. The listening experience of audio which has passed through a perceptually coded system is not best characterized by many of the normal objective audio quality measures such as signal-to-noise, distortion, or bandwidth. The instruments used to make such measurements do not adequately respond to the perceptual aspects of the system. This is one of the reasons why the NRSC's test program includes such a comprehensive subjective evaluation component.[10]

3.1 iBiquity FM IBOC system

The iBiquity FM IBOC system supports transmission of digital audio and auxiliary digital data within an existing FM channel allocation by placing two groups of digitally modulated carrier signals adjacent to an analog FM signal as shown in Figure 1. These sideband groups are independent in that only one group (either USB or LSB in the figure) is needed for an IBOC receiver to be able to generate digital audio. Orthogonal frequency division multiplexing ("OFDM") modulation is utilized. The digital audio modulated onto these OFDM carriers is perceptually coded, allowing for high-quality digital audio using a relatively low bit rate (96 kbps was the digital audio bit rate used for the NRSC tests).

[10] See IBOC FM Test Data Report, Appendix H, for a detailed description of the subjective testing methodology used in the NRSC's test program.

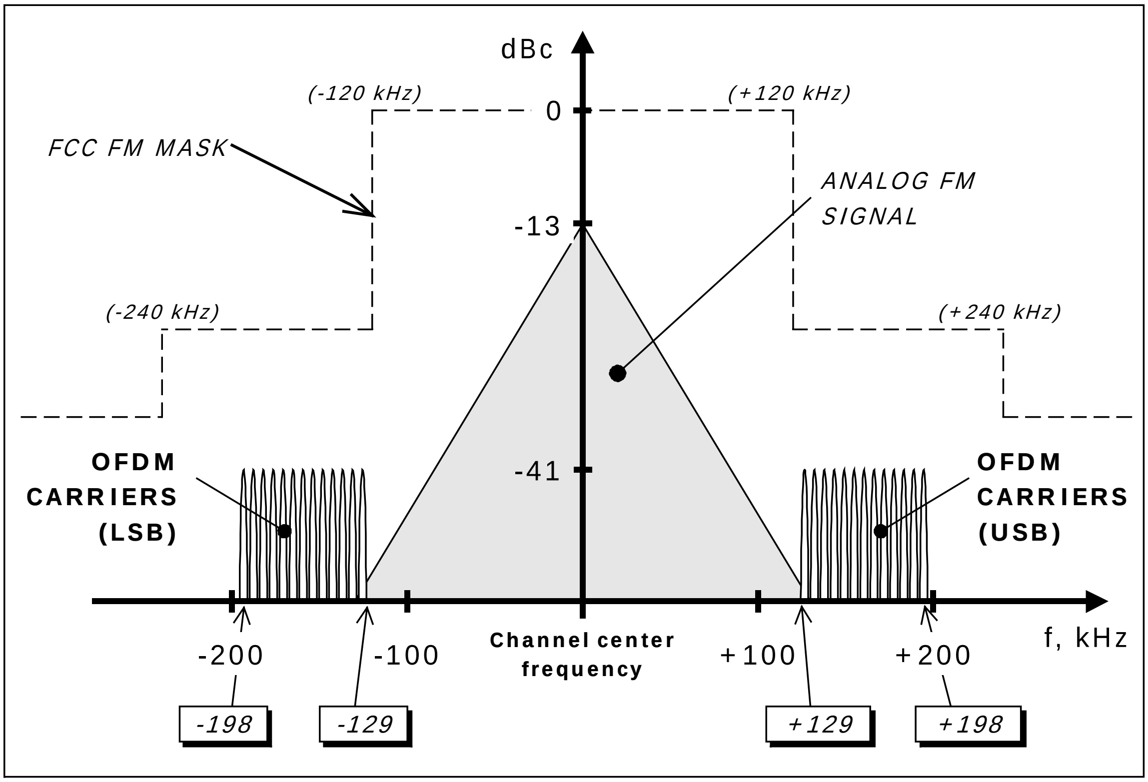

Figure 1. iBiquity FM IBOC system signal spectral power density

A complete description of the FM IBOC signal is given in the IBOC FM Test Data Report.[11] This system incorporates a 4 1/2 second delay between the analog and digital (simulcast) audio signals to improve performance in the presence of certain types of interference, which may affect how broadcasters monitor off-air signals.[12] Some of the specific attributes of this system which influenced the design of the NRSC's test program are listed here:

- Proximity of digital sidebands to 1st-adjacent channel signals: the digital sidebands of the FM IBOC signal are located such that they could potentially interfere with (and receive interference from) a 1st-adjacent analog FM signal (Figure 2). The NRSC test procedures include tests which characterize this behavior, including tests of IBOC performance when there are two 1st-adjacent channel signals, one on either side of the desired signal (hence both digital sidebands are experiencing interference).

[11] See IBOC FM Test Data Report, Appendix A ("IBOC FM Transmission Specification").
[12] For additional information on this see IBOC FM Test Data Report, Appendix A, pg. 4.

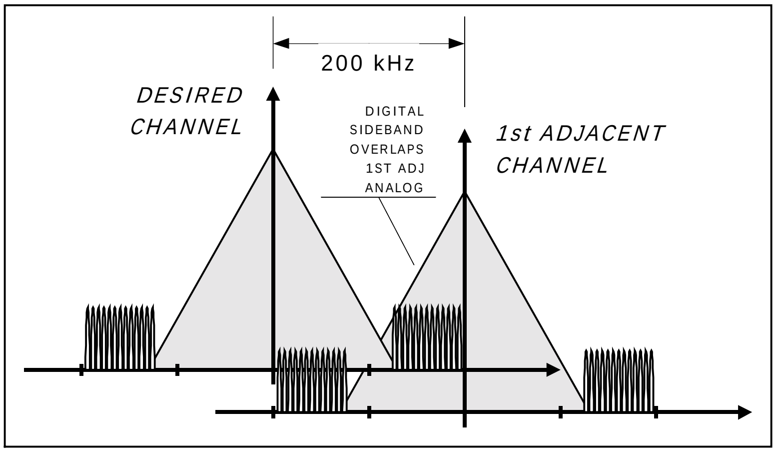

Figure 2. Illustration of potential interference to/from 1st-adjacent analog signals by FM IBOC digital sidebands

- Proximity of digital sidebands to 2nd-adjacent channel signals: the FM IBOC system design allows for approximately 4 kHz of "guard band" between 2nd-adjacent IBOC digital sidebands (Figure 3). Because this relatively close proximity could have an impact on performance, the NRSC test procedures include tests for characterizing performance with 2nd-adjacent interference, including dual 2nd-adjacent channel interferers with power levels up to 40 dB greater than the desired signal power (since FCC rules allow a 2nd-adjacent signal to be 40 dB stronger than the desired signal at the desired signal's protected contour).

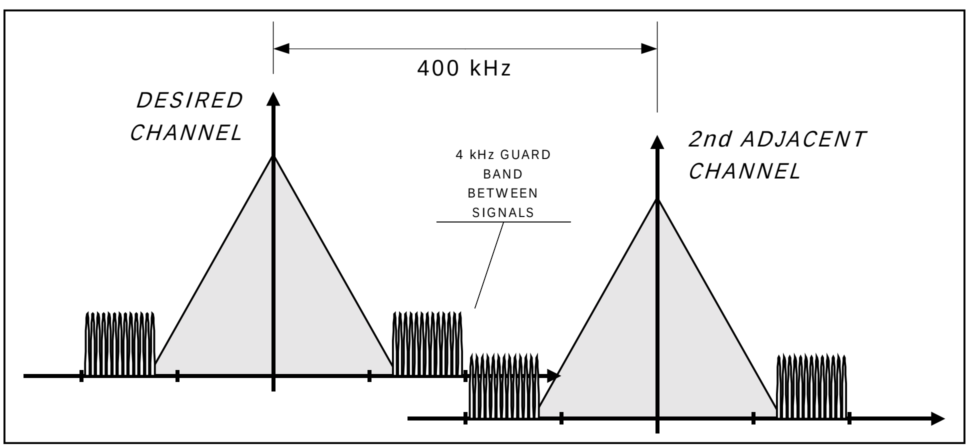

Figure 3. Illustration of potential interference between 2nd-adjacent FM IBOC signals

- Blend-to-analog: the iBiquity FM IBOC system simulcasts a radio station's main channel audio signal using the analog FM carrier and IBOC digital sidebands, and under certain circumstances, the IBOC receiver will "blend" back and forth between these two signals. Consequently, depending upon the reception environment, the listener will either hear digital audio (transported over the IBOC digital sidebands) or analog audio (delivered on the FM-modulated analog carrier), with the digital audio being the primary condition.

  The two main circumstances under which an IBOC receiver reverts to analog audio output are during acquisition i.e. when a radio station is first tuned in (an IBOC receiver acquires the analog signal in milliseconds but takes a few seconds to begin decoding the audio on the digital sidebands), or, when reception conditions deteriorate to the point where approximately 10% of the data blocks sent in the digital sidebands are corrupted during transmission. Many of the tests in the NRSC procedures are designed to determine the conditions which cause blend-to-analog to occur in this second circumstance, since at this point the IBOC system essentially reverts to analog FM.

iBiquity has indicated that the analog section of the prototype IBOC receiver used for the NRSC tests is a "software radio" and has not yet been optimized to the point where it performs commensurate with existing analog radios (automotive radios in particular). Consequently, the NRSC elected not to do any evaluations on the IBOC receiver output after it had blended to analog, but instead, would evaluate the output of an existing analog receiver operating under the same signal conditions as those which resulted in blend-to-analog in the IBOC receiver, when such evaluation was required. Typically, tests specify recording of the IBOC receiver output just before (with respect to the test conditions) it blends to analog, guaranteeing that it will be operating in digital audio mode, and recording of the audio from an existing analog receiver under identical conditions, then these recordings are subjectively evaluated so that digital and analog receiver performance near the (IBOC receiver) point of blend-to-analog can be compared.

3.2 Lab tests

Laboratory tests are fundamental to any characterization of a new broadcast system such as FM IBOC. The controlled and repeatable environment of a laboratory makes it possible to determine how the system behaves with respect to individual factors such as presence or absence of RF noise, multipath interference, or co- and adjacent-channel signals. These factors all exist in the "real world" but because they exist simultaneously and are constantly changing, it is virtually impossible to determine, in the "real world," the effect each has on system operation.

For the NRSC test program, an independent testing facility—the Advanced Television Technology Center (ATTC)—was selected to conduct all laboratory tests. Prior to testing, the ATTC developed and carried out a test bed "proof of performance" plan, and submitted the results of this proof to the NRSC.[13] As discussed above in Section 1, NRSC observers were present for the vast majority of all lab tests conducted at ATTC. The ATTC was also involved in preparing the recorded audio cuts for the subjective evaluation which was done by another independent testing contractor, Dynastat, Inc.

3.3 Field tests

Field testing of a new broadcast system is necessary to determine performance in "the real world" where all of the various factors which impact propagation and reception of radio signals exist to varying degrees depending upon time of day, geographic location and environmental factors. For the NRSC test program, eight FM stations were selected for use in field testing (Table 4).

[13] See "Digital Audio Broadcasting – Test Bed Proof-of-performance Plan," ATTC doc. no. 00-05, December 2000, rev. 1.1, and "Digital Audio Broadcasting – Test Bed Proof-of-performance," ATTC doc. no. 01-01, January 2001, rev. 1.0.

Table 4. FM IBOC field test stations

STATION	FORMAT	LOCATION	PRINCIPLE TEST CONDITION(S) †	COMMENTS
WETA 90.9	Talk and classical	Washington, D.C.	(a) low interference and low multipath	• Chan. 215B - # of radials - 8 • Host compatibility
WPOC 93.1	Country	Baltimore, MD	(c) single first adjacent interferer	• Chan. 226B - # of radials - 5 • Host, 1st-adj. compatibility (WMMR, WFLS)
WD2XAB 93.5	Test	Columbia, MD	(d) single second adjacent interferer	• Chan. 228A – limited testing • 2nd-adj. tests (WPOC is 2nd-adj. IBOC interferer)
KLLC 97.3	"Alice" (contem-porary rock)	San Francisco, CA	(b) low interference, moderate/strong multipath (f) terrain obstructions	• Chan. 247B - # of test loops – 5 • EIA/NRSC test routes used (from 1996 tests) – routes are loops (not radials)
WHFS 99.1	Rock	Annapolis, MD	(e) simultaneous dual interferers, to the extent feasible	• Chan 256B - # of radials – 1 (towards 2nd-adj's) • Two strong 2nd-adj. interferers (WMZQ, WJMO)
KWNR 95.5	Country	Las Vegas, NV	(b) low interference, moderate/strong multipath (f) terrain obstructions	• Chan 238C - # of radials - 8 • "Specular" multipath (Las Vegas "Strip")
WNEW 102.7	Talk and Rock	New York, NY	(b) low interference, moderate/strong multipath (g) centrally-located urban antenna (h) combined antenna (i) strong single 1st adjacent interferer	• Chan. 274B # of radials – 4 (also "urban circles") • 1st-adj. compatibility (WMGK) • "Specular" multipath (downtown NYC) • Antenna located on top of Empire State Building
WWIN 95.9	Urban (pop)	Baltimore, MD	(d) single second adjacent interferer (j) low power combiner/common amp. (k) class A FM facility	• Chan 240A - # of radials – 4 • Only station to use low power combiner (other stations all use high-power combiner)

†letters in parentheses refer to test condition designations used in FM field test procedures.

Data collection in the field was done using test vehicles provided by iBiquity Digital Corporation (one such vehicle is shown in Figure 4 and Figure 5). These vehicles were outfitted with an array of test equipment and computers, and utilized four analog FM receivers (see Table 6) and an iBiquity FM IBOC prototype receiver for capturing analog and IBOC radio transmissions, respectively.

Figure 4. Field test vehicle (provided by iBiquity Digital Corporation)

Figure 5. Interior view of field test vehicle showing analog and IBOC receivers, computer, and test equipment

NRSC field test observers were present during collection of all field test data, which was collected principally with the test vehicle in motion, although most of the analog compatibility measurements done in the field were done with the test vehicle stationary. NRSC observers also participated in the preparation of audio cuts obtained in the field for subjective evaluation. As was true for the laboratory tests, an independent test contractor, Dynastat, Inc., conducted the subjective evaluations.

3.4 Analog FM receivers

Four commercially-available analog FM receivers were used for compatibility testing of main channel audio services (see Table 6 below). These receivers were chosen to be representative of the vast majority of receivers used in the U.S. In December, 2000, CEA's Market Research Department provided the NRSC with the names of three of the top five brands, listed alphabetically, for each of three general receiver categories (Table 5), indicating that any model of radio from one of the brands indicated in Table 5 would represent one of the top-selling models in the U.S. in December, 2000.

Table 5. CEA AM/FM receiver market research results – December 2000

RECEIVER TYPE	3 OF TOP 5 BRANDS
Home (hi-fi)	Pioneer, Sony, Technics
CD boom box	Aiwa, Philips, Sony
Auto aftermarket CD	Kenwood, Pioneer, Sony

To determine if a single radio from each category would be sufficient to predict the performance of all radios in that category, advice was sought from Mr. Jon Grosjean, an expert on radio receivers who frequently provides consulting services to radio receiver manufacturers. According to Mr. Grosjean, the tuning circuitry inside modern FM radios generally falls into three categories that are defined by selectivity, specifically: "moderately selective" receivers, "selective" receivers, and "very selective" receivers. Mr. Grosjean said that clock, personal, and portable radios marketed in the U.S. are generally moderately selective, and as a result are least adept at rejecting adjacent channel interference.

Regarding home stereo receivers, Mr. Grosjean said these are generally selective and are good at rejecting adjacent channel interference, though he noted there may be a few inexpensive home stereo receivers on the market that are only moderately selective, and there may be a few very expensive home stereo receivers on the market that are very selective, though these would be the exception for this category. And for automotive radios, Mr. Grosjean indicated these are generally very selective, though there may be some models on the market that are simply selective. Generally speaking, Mr. Grosjean felt that OEM radios are usually the most selective, though aftermarket radios appear to have shown a tendency towards greater selectivity in recent years.

In light of the CEA receiver market data, and Mr. Grosjean's insights into receiver design, the NRSC selected the receivers listed in Table 6 for compatibility testing. The Pioneer, Sony and Technics receivers were available in Washington, DC area retail stores in December, 2000, and the Delphi OEM receiver was being installed in automobiles in December, 2000. All four were examined by Mr. Grosjean. They were also examined by Mr. Robert McCutcheon, who has performed extensive radio receiver tests for the NRSC in the past.[14] Both Mr. Grosjean and Mr. McCutcheon confirmed that these radios were representative of their respective categories.

Table 6. Analog FM receivers used in the NRSC test program

MANUFACTURER	MODEL NO.	TYPE	COMMENTS
Delphi	09394139	OEM automotive receiver	Very selective
Pioneer	KEH-1900	Aftermarket automotive receiver	Very selective
Sony	CFD-22S	Portable radio	Moderately selective
Technics	SA-EX140	Home stereo receiver	Selective

3.5 Analog subcarrier receivers

In the fall of 2000, the Test Procedures Working Group (TPWG) of the NRSC's DAB Subcommittee needed to select a limited number of 67 kHz and 92 kHz analog SCA receivers for use in the NRSC FM IBOC test program. One of the group's members, the International Association of Audio Information Services (IAAIS), Mr. Dave Andrews, representative, offered to study this matter and make recommendations in this area. This offer was appreciated by the TPWG since IAAIS represents individuals who are major users of the SCA receivers in question.

Using the IAAIS-operated, Internet-based listserv, Mr. Andrews conducted an informal survey of IAAIS members to determine which receivers (make and model, and SCA frequency, in particular) were used and in what numbers. He was then able to rank the receivers according to frequency of use and selected the four units most commonly used (Table 7) which are the receivers the NRSC ultimately selected.

Table 7. Analog SCA receivers used in the NRSC test program

MANUFACTURER	MODEL NO.	SUBCARRIER FREQUENCY
McMartin	TRE5	67 kHz
Norver	Nu-1C	67 kHz
CozmoCom	HL922	92 kHz
Compol	SCA-BL	92 kHz

Of the four receivers listed in Table 7, two are no longer manufactured, but are still in the field in large numbers. These are the McMartin and the Norver units. The second two receivers, the CozmoCom and the Compol are widely used by radio reading services and both companies are still active in the field. Furthermore, the CozmoCom unit is also widely used by listeners of ethnic SCA broadcast services.

3.6 Digital subcarrier receivers

The EWG elected to perform compatibility tests on two types of digital subcarriers: Radio Data System (RDS) subcarriers, standardized for North American broadcasters under the NRSC's RBDS

[14] See Appendix D for data resulting from Mr. McCutcheon's examination.

Standard,[15] and the DAta Radio Channel (DARC) subcarrier, developed by NHK of Japan and used worldwide, most notably in the U.S. by CUE Corporation. For the RDS tests, an Audemat integrated RDS receiver was used; for DARC, a Sectra DRB-3000 DARC receiver was used. These receivers were selected primarily because the software used to support them would allow for observation and recording of the block error rate (BLER) performance of the receivers during operation, the principal benchmark of performance used for the NRSC's digital subcarrier receiver tests.

[15] See "United States RBDS Standard," April, 1998 (published by the NRSC).

4 DISCUSSION OF FINDINGS

In this section a detailed explanation of the EWG's review of test data submitted to the NRSC will be presented. References are made throughout to specific test results from the FM IBOC Test Data Report, in particular in summary tables (*e.g.*, Table 10) given at the beginning of many of the sub-sections below. In these tables, references to page numbers, appendices, figures, tables, and so forth, are taken from the FM IBOC Test Data Report, and are provided here to identify specific test results that the EWG used during its evaluation. The findings presented here, and for that matter every aspect of the NRSC's IBOC test program, have been divided into two specific areas - *digital performance* and *analog compatibility*.

4.1 Digital performance

Digital performance refers to the performance of the IBOC digital radio system itself. As discussed below in Section 4.3, eight specific areas of digital performance have been considered by the EWG. All of the test results obtained on digital performance were obtained using an iBiquity prototype IBOC receiver (Figure 6) or through direct observation of the received signal. At least three examples of the iBiquity IBOC receiver were used during testing – one each in two separate field test vehicles, and one in the laboratory.

Figure 6. iBiquity prototype receiver –as used in field test vehicle (receiver is rectangular black box in upper right-hand corner of rack)

In evaluating the digital performance of the system, the EWG's task was to determine if the digital performance demonstrated by the test results was a "significant improvement over existing analog services," as directed by the Subcommittee's Goals and Objectives statement. Guiding the EWG as it attempted to determine this was a set of performance goals it developed (Table 8) defining in more concrete terms what a "significant improvement over existing analog services" consists of.

Table 8. FM IBOC performance goals as established by the EWG

CATEGORY		PERFORMANCE GOALS – FM IBOC
Fidelity	Frequency response & distortion	Frequency response & distortion fidelity should be comparable to or better than the best FM
		To alleviate the effects of channel impairments and interference, it may be acceptable to diminish distortion and frequency response fidelity to maintain audio free of dropouts and noticeable artifacts.
	Noise	May be acceptable to compromise noise fidelity to maintain dropout- and artifact-free audio
	Stereo separation	May be acceptable to compromise in response to channel impairments
	Fidelity of digital technologies	a) Source coding should not cause artifacts that noticeably reduce fidelity throughout the service area b) Should have sufficient apparent dynamic range so that low level and dynamic content reproduce with the same fidelity as aggressively processed audio
Durability	Interference	Digital systems should reach a service area that matches or exceeds actual interference-limited service area of the analog host
	Impairments	Digital technology will be considered to be better than analog against impairments if digital multipath and fade artifacts have the following characteristics: a) They are demonstrably less objectionable, less frequent in time and less prevalent in location than those of analog services b) They maintain higher fidelity than analog for a preponderance of occurrences c) They result in fewer total losses of intelligible audio than analog, and recovery from total loss is not significantly longer than analog in similar circumstances
Flexibility	Flexibility of transmission systems *(includes COMPATIBILITY with existing analog services)*	A successful digital technology will: a) Reasonably protect the performance and flexibility of its analog host and adjacent channel stations (i.e. is compatible with existing analog services); b) Provide a platform that can be improved in software, firmware and hardware in a manner that is compatible with its original technology; c) Give broadcasters tools to create features to enhance the listener experience and permit the medium to remain relevant and competitive in the coming decades.

In anticipation of the need for a comparison between analog and digital performance, the NRSC's test procedures in most cases require the collection of analog data (using existing analog FM receivers) and hybrid IBOC data (using the iBiquity prototype IBOC receiver) either simultaneously (utilizing the IBOC host as the analog signal) or sequentially (for example, in the laboratory), such that a valid comparison could be made. Figure 7 offers a perfect example of how this approach can lead to a meaningful comparison of IBOC and analog from which conclusions about digital performance can be drawn.

In this figure, the subjective evaluation scores[16] of audio samples collected in the field, for both FM IBOC and analog, have been plotted by program type illustrating the differences perceived by listeners between digital and analog performance. Note that the analog and digital audio cuts evaluated were obtained simultaneously under identical reception conditions (four and one-half second time delay between analog and digital notwithstanding)—this is possible since the transmitted audio is simulcast on the IBOC and analog signals—and that consequently this data offers an excellent opportunity to fairly and accurately compare digital and analog performance. Referring to the figure, the data indicate that while the analog quality is in the "fair" range, the IBOC quality is in the "good" to "excellent" range, representing a very significant difference between the two. Clearly, this data suggests that for all program types tested, the digital performance was a consistent and significant improvement over the analog.

[16]The evaluation scores are expressed in terms of Mean Opinion Score ("MOS"), a rating of audio quality. For these tests, the MOS scale used was 5=Excellent, 4=Good, 3=Fair, 2=Poor, 1=Bad. Additional information on the subjective evaluation methods used in this evaluation may be found in Appendix H of the FM IBOC Test Data Report.

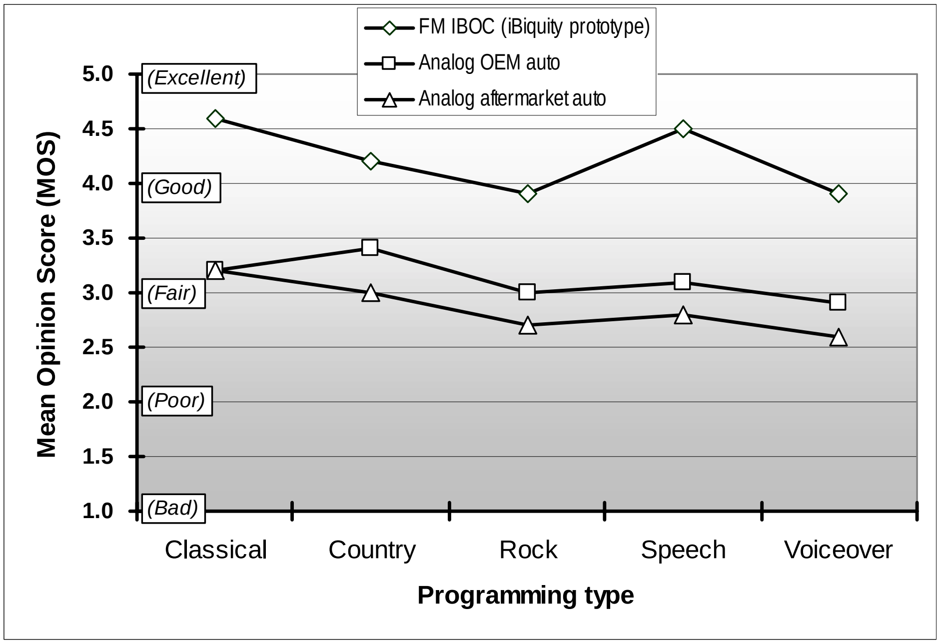

Figure 7. Comparison of FM IBOC and analog audio subjective evaluation results aggregating all field test conditions[17]

Another good example of how the EWG was able to compare digital and analog performance is shown in Figure 8, taken from Appendix K of the FM IBOC Test Data Report, the so-called “ticker test” (discussed more fully below in Section 4.5.8). These results are also subjective in nature, and compare the number of “impairments” (ticks, pops, clicks, etc.) heard by listeners on field test audio obtained simultaneously on an IBOC and on two automotive analog FM receivers (the same receivers for which data was presented in Figure 7). As discussed above for Figure 7, because the digital and analog audio recordings were made simultaneously under identical reception conditions (four and one-half second time delay between analog and digital notwithstanding), the results are directly comparable, and again, there is strong evidence that the digital performance is a significant improvement over the performance offered by analog FM, since so many fewer impairments were heard in the IBOC signal.

[17] Taken from pg. 9 of main text of iBiquity Digital Corporation report to the NRSC, August 2001, with minor modification.

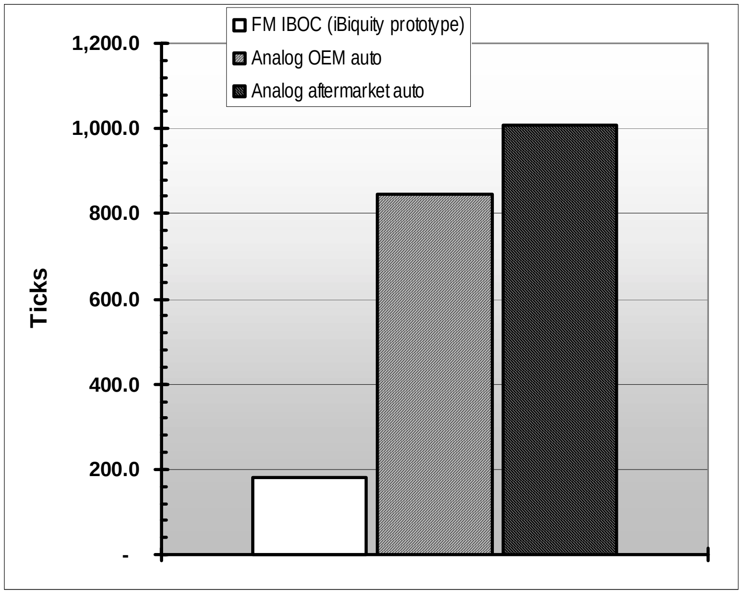

Figure 8. Comparison of FM IBOC and analog (automotive) receivers using "ticker" test - each "tick" corresponds to an audio impairment heard by a listener

4.2 Analog compatibility

The other area of investigation undertaken by the EWG is that of *analog compatibility*. Analog compatibility pertains to the effect that the IBOC digital radio signal has on reception of existing analog signals (both main channel audio and subcarriers). Because of the fact that an FM IBOC signal adds additional energy within a radio station's existing frequency allocation (see Figure 1 above) it is reasonable to expect that analog receivers, not designed with this extra signal energy in mind, may experience interference from this additional energy. The role of the NRSC here is to confirm that IBOC has either no impact or an "acceptable" impact on how existing analog signals are received.

Whether or not interference will exist depends on a variety of factors, one of the most important being the signal level of the IBOC digital sidebands with respect to the host analog signal. This is a critical parameter—the sideband level must be set high enough to provide for good digital coverage, but low enough so that the impact on analog signals is minimized—and is in fact one of the most difficult tradeoffs that IBOC system designers have to deal with.

There are three general types of compatibility – host, first adjacent channel, and second adjacent channel. Host compatibility relates to the impact the IBOC system has on analog reception of the station the IBOC system is installed on. 1st-adjacent channel compatibility relates to the impact the IBOC system has on analog reception of a station located 200 kHz above (or below) the station broadcasting the IBOC signal (see Figure 2 above). Similarly, 2nd-adjacent channel compatibility relates to the impact the IBOC system has on analog reception of a station located 400 kHz above (or below) the station broadcasting the analog signal (see Figure 3 above). Two examples of compatibility as measured in the field under this test program are provided in Figure 9 and Figure 10, for host and 1st adjacent channel compatibility, respectively.

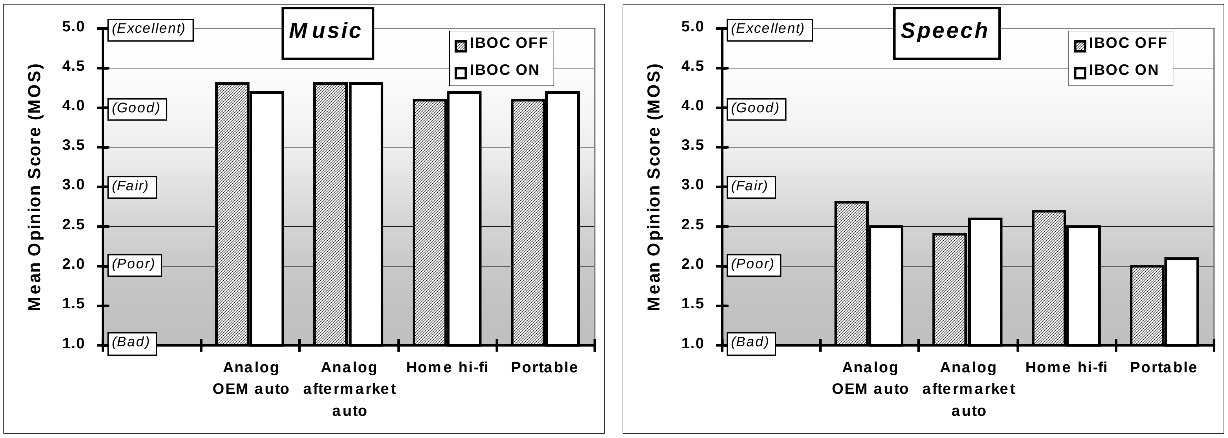

Figure 9. Host compatibility – subjective evaluation results of audio recordings obtained in the field

As in Figure 7 above, these figures present subjective evaluation results obtained on field test recordings of the main channel audio signal. For each figure, results are presented for some or all of the analog receivers used in NRSC testing. For each set of test parameters (e.g., program type, amount of interference) note how the receivers perform differently from one another under identical test conditions, illustrating one reason why it was important for the NRSC to carefully select the analog receivers (as discussed in Section 3.4 above). In
Figure 9, it is also interesting to note that the perceived audio quality, whether or not the IBOC sidebands are present, is highly dependent upon the type of programming being listened to. Specifically, "music" programming rated much higher (in the "good" range) than did "speech" programming (in the "poor" to "fair" range), under similar conditions. Overall, the small differences between "IBOC on" and "IBOC off" in Figure 9 indicate that the impact of the IBOC digital sidebands on the host analog signal is slight.

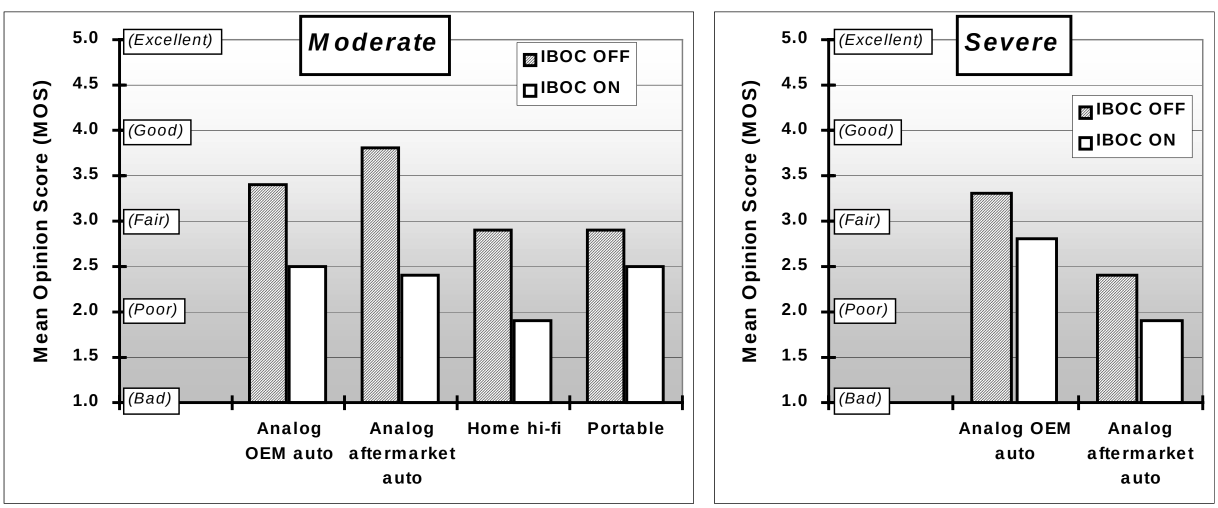

Figure 10. 1st-adjacent compatibility - subjective evaluation results of audio recordings obtained in the field (speech programming)
Moderate: +16 to +6 dB D/U
Severe: +6 to –9 dB D/U

The results shown in Figure 10 serve to illustrate one of the greatest compatibility challenges facing FM IBOC, operation with 1st-adjacent channel interference (discussed in greater detail below in Section 4.12.2), and were obtained in the presence of moderate (between +16 and +6 dB D/U) and severe (between +6 and –9 dB D/U) 1st-adjacent channel interference. These results indicate that under certain circumstances, for certain radios, the presence of the IBOC digital sidebands will have a noticeable effect on analog receiver audio quality. For example, the audio quality of the analog aftermarket auto radio, under moderate interference conditions, is reduced from the "good" range (with no IBOC present) to the "poor" range (with the IBOC digital sidebands present on a 1st-adjacent channel interferer).

By comparing the difference between the "IBOC off" and "IBOC on" performance for the analog OEM auto radio and the analog aftermarket auto radio shown in Figure 10, for the moderate and severe cases, one of the performance behaviors of analog radios which affects compatibility is highlighted—as the interference level increases, the impact of the IBOC digital sidebands on analog receiver performance becomes less noticeable. Specifically, notice how the difference between IBOC on and IBOC off for the analog aftermarket auto radio (in terms of MOS) is about 1.5 in the moderate case, but only about 0.5 for the severe case, a significant reduction.

This last point, that the amount of interference has a bearing on compatibility, has important ramifications for laboratory testing, since one important interference signal which exists in all radio reception environments, that of RF "background noise," is not normally present when co- and adjacent-channel laboratory tests are performed. Because of this, the NRSC decided to add a background noise component to the RF signals under test during compatibility testing, so that the results of subsequent subjective evaluation would be more realistic. The actual amount of RF white noise added, corresponding to 30,000K, was based on studies done by iBiquity.[18] Lab measurements were also made with no added noise as a "sanity check," providing a baseline for comparison in case the results with the artificial noise added turned out to be very different than the real world results obtained in the field. As was expected, the 30,000K results did not turn out to be very different from the field results.

4.3 Evaluation criteria

The EWG utilized 10 criteria for evaluating the data contained in the FM IBOC Test Data Report. Each criterion falls into one of the (previously mentioned) two general categories of results: "digital performance," which applies to performance of the IBOC digital signal, and "analog compatibility," which addresses the impact of the IBOC signal on reception with existing analog receivers. Table 9 lists the evaluation criteria according to category; refer to Appendix E for a detailed description of each criterion, and to Appendix F for a matrix that illustrates which tests (contained in the test procedures) have a bearing upon which criteria.

[18] A summary of these studies was prepared for the NRSC by iBiquity - see "NRSC Noise Report," November 2001.

Table 9. EWG evaluation criteria

DIGITAL PERFORMANCE	ANALOG COMPATIBILITY
Audio quality Service area Durability Acquisition performance Auxiliary data capacity Behavior as signal degrades Stereo separation Flexibility	Host analog signal impact Non-host analog signal impact

As previously mentioned, the goals listed in Table 8 above were used to guide the EWG's assessment of how the IBOC system performed compared to existing analog services. In many cases (as is noted in the "analog benchmark" columns of the test result tables below, *e.g.*, Table 10) analog benchmark data was collected along with the IBOC system data; for compatibility tests, the "IBOC off" data was used as a benchmark (and compared against the "IBOC on" data obtained under otherwise identical conditions, four and one-half second time delay between analog and digital notwithstanding).

4.4 Criterion 1 – Audio quality

Table 10 lists the test results pertaining to audio quality of the iBiquity FM IBOC system.

Table 10. FM IBOC test results pertaining to audio quality

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Field - various	n/a	Appendix K: - Fig. 1, pg. 2 - Figs. 2-9, pgs. 4-11 - Fig. 10, pg. 12	Impairments observed in automotive receivers	"Ticker test" - audio from analog receivers contained 4-5 times more impairment events (6-7 times the number of severe impairment events) than audio from IBOC receivers
Field – various	n/a	Main report: - Fig. 1, pg. 9	Audio quality of automotive receivers	Subjective evaluation of field test data – aggregated results

As defined by the EWG, this criterion relates specifically to the audio quality of the main channel audio signal received under unimpaired conditions i.e. in the absence of RF noise, interfering signals, multipath interference, weak signal conditions, or any other circumstance which would adversely affect reception. Because the results of such tests are in effect a test of the perceptual audio coding algorithm used, and because the iBiquity system hardware tested for the purposes of this evaluation did not utilize the audio coding algorithm to be used in the final deployed version of the system, the NRSC is, strictly speaking, not able to come to any conclusions for this criteria.

However, subjective evaluations of audio obtained in the field (for example, Figure 7 above) strongly suggest that the audio quality of IBOC digital audio will be a significant improvement over the audio quality of existing FM analog if the definition of audio quality is expanded to include that experienced by mobile radio listeners. This of course assumes that the performance of the iBiquity audio coding algorithm meets or exceeds that of the MPEG-2 AAC algorithm used in the hardware tested by the NRSC.

4.4.1 Findings

The iBiquity hybrid FM IBOC system with MPEG-2 AAC perceptual audio coding demonstrates significantly improved audio quality compared to existing analog FM in mobile listening environments. Since the final version of this system will utilize a proprietary iBiquity perceptual audio coding algorithm and not MPEG-2 AAC, no direct findings on the unimpaired audio quality of the final system can be made at this time.

4.5 Criteria 2, 3 – Service area, durability

Table 11 lists the test results pertaining to service area and durability of the iBiquity FM IBOC system. These two criteria have been combined in this section because they essentially share the same list of tests (from the test procedures) from which conclusions can be drawn.

Table 11. FM IBOC test results pertaining to service area and durability

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab - B.1 - AWGN	Appendix D: - Fig. 1, pg. 25	Appendix D: - Tables 13, 14, pg. 24 Appendix I, pg. 21	None	Classical music audio quality (fair to good) rated poorer than rock, speech (good to excellent)
Lab – B.2 – Multipath with noise	Appendix D: - Fig. 2, pg. 27 (urban slow) - Fig. 3, pg. 27 (urban fast) - Fig. 4, pg. 28 (terrain obstructed) - Fig. 5, pg. 28 (rural fast)	Appendix D: - Tables 15, 16, pg. 26 Appendix I, pg. 21	Subjective only – MOS scores for automotive receivers	IBOC audio quality good to excellent while analog poor to fair for all cases
Lab – C.1 – Impulse noise	Appendix D: - Fig. 6, pg. 30 (120 Hz) - Fig. 7, pg. 30 (120 Hz, 1st adj.) - Fig. 8, pg. 31 (330 Hz) - Fig. 9, pg. 31 (330 Hz, 1st adj.) - Fig. 10, pg. 32 (510 Hz) - Fig. 11, pg. 32 (510 Hz, 1st adj.) - Fig. 12, pg. 33 (1200 Hz) - Fig. 13, pg. 33 (1200 Hz, 1st adj.) - Fig. 14, pg. 34 (1800 Hz) - Fig. 15, pg. 35 (1800 Hz, 1st adj.) - Fig. 16, pg. 35 (2000 Hz) - Fig. 17, pg. 35 (2000 Hz, 1st adj.) - Fig. 18, pg. 36 (PN) - Fig. 19, pg. 36 (PN, 1st adj.)	Appendix D: - Table 18, pg. 37 Appendix I, pg. 26	Subjective only – MOS scores for automotive receivers (only classical program material used)	No 1st-adj. chan. interferer - IBOC audio quality good to excellent while analog poor to good for all cases With +6 dB upper 1st-adj. (hybrid for digital cases, analog for analog cases): - 120, 330 Hz: IBOC audio quality good to excellent while analog poor to good - 510 Hz, 1200 Hz, 1800 Hz, 2000 Hz, PN: IBOC blending to analog

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab – C.2 – Airplane flutter	Appendix D: - Table 19, pg. 38	Appendix D: - Table 20, pg. 38 Appendix I, pg. 27	Subjective only – MOS scores for automotive receivers (only classical program material used)	IBOC BLER equaled zero for all cases tested IBOC audio quality good to excellent while analog bad to poor for all cases
Lab – D.1 – Co-channel IBOC ➜ IBOC	Appendix D: - Fig. 20, pg. 39	Appendix D: - Table 22, pg. 40 Appendix I, pg. 22	Subjective only – MOS scores for all 4 analog receivers (only classical program material used)	Blend D/U point +2 dB IBOC audio quality good to excellent while analog failed or bad
Lab – D.2 – Single and dual 1st adjacent IBOC ➜ IBOC	Appendix D: - Fig. 21, pg. 41 (single 1st) - Fig. 22, pg. 41 (dual 1st)	Appendix D: - Table 24, pg. 40 Appendix I, pg. 22, 23	Subjective only – MOS scores for all 4 analog receivers	Blend D/U point, single 1st: -30 dB; dual 1st: +21 dB IBOC audio quality, single 1st: good to excellent while analog failed or bad IBOC audio quality, dual 1st: good while analog either good (auto) or bad to poor (home, portable)
Lab – D.3 – Single and dual 2nd adjacent, simultaneous single 2nd and single 1st adjacent IBOC ➜ IBOC	Appendix D: - Fig. 23, pg. 42 (single 2nd) - Fig. 24, pg. 43 (single 2nd and single 1st) - Fig. 25, pg. 43 (dual 2nd)	Appendix D: - Table 26, pg. 44 Appendix I, pg. 22, 23	Subjective only – MOS scores for all 4 analog receivers	Blend D/U point: greater than –42 dB (test bed power limit – IBOC never blended) IBOC audio quality, single or dual 2nd: good while analog were failed IBOC audio quality, single 1st and single 2nd: fair to good while analog were failed
Lab – E.1 - Co-channel IBOC ➜ IBOC with multipath	Appendix D: - Fig. 26, pg. 46 (urban slow) - Fig. 27, pg. 46 (urban fast) - Fig. 28, pg. 47 (terr. obstructed) - Fig. 29, pg. 47 (rural fast)	Appendix D: - Table 28, pg. 48 Appendix I, pg. 24	Subjective only – MOS scores for automotive receivers	Blend D/U point: 6-8 dB higher than no multipath case IBOC audio quality good to excellent while analog bad to poor
Lab – E.2 – Single and dual 1st adjacent IBOC ➜ IBOC with multipath (US – urban slow UF – rural fast TO – terrain obstructed RF – rural fast)	Appendix D: - Fig. 30, pg. 49 (US, single 1st) - Fig. 31, pg. 50 (UF, single 1st) - Fig. 32, pg. 50 (TO, single 1st) - Fig. 33, pg. 51 (RF, single 1st) - Fig. 34, pg. 51 (US, dual 1st) - Fig. 35, pg. 52 (UF, dual 1st) - Fig. 36, pg. 52 (TO, dual 1st) - Fig. 37, pg. 53 (RF, dual 1st)	Appendix D: - Table 30, pg. 53-54 Appendix I, pg. 24	Subjective only – MOS scores for automotive receivers	Blend D/U point, single 1st: approx. 21-25 dB higher than no multipath case; dual 1st: approx. 15 dB higher than no multipath case except for terrain obstructed which is 30 dB higher IBOC audio quality, single 1st: good to excellent while analog poor to fair. IBOC audio quality, dual 1st: good to excellent while analog poor to good.

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab – E.3 – Single and dual 2nd adjacent, simultaneous single 2nd and single 1st adjacent IBOC ➜ IBOC with multipath (US – urban slow UF – rural fast TO – terrain obstructed RF – rural fast)	Appendix D: - Fig. 38, pg. 56 (US, single 2nd) - Fig. 39, pg. 56 (UF, single 2nd) - Fig. 40, pg. 57 (TO, single 2nd) - Fig. 41, pg. 57 (RF, single 2nd) - Fig. 42, pg. 58 (US, single 2nd and single 1st) - Fig. 43, pg. 58 (UF, single 2nd and single 1st) - Fig. 44, pg. 59 (TO, single 2nd and single 1st) - Fig. 45, pg. 59 (RF, single 2nd and single 1st) - Fig. 46, pg. 60 (US, dual 2nd) - Fig. 47, pg. 60 (UF, dual 2nd) - Fig. 48, pg. 61 (TO, dual 2nd) - Fig. 49, pg. 61 (RF, dual 2nd)	Appendix D: - Table 32, pg. 62-63 Appendix I, pg. 25	Subjective only – MOS scores for automotive receivers	Single 1st and single 2nd terrain obstructed case – performance vs. D/U is flat IBOC audio quality, single 2nd: good to excellent while analog fair to good. IBOC audio quality, single 2nd and single 1st: blending to analog for terrain obstructed case, otherwise good while analog poor to fair. IBOC audio quality, dual 2nd: good to excellent while analog fair to good.
Field – B.1, B.2 – System performance - low interference and low multipath, 1st adj. channel interference	Main report: - Table 5, pg. 13 (list of 1st-adj interferers) - Fig. 8, pg. 18 (KWNR – perf. on Las Vegas Blvd.) - Fig. 9, pg. 19 (WNEW – perf. in downtown NYC) - Fig. 10, pg. 20 (KLLC – perf. in downtown SF) – Fig. 11, pg. 21 (WHFS – perf. in downtown Wash., DC) - Fig. 12, pg. 22 (WWIN digital coverage vs. interferers) Appendix F1 (WETA cov. maps) Appendix F2 (WPOC cov. maps) Appendix F3 (WHFS cov. maps) Appendix F4 (WNEW cov. maps) Appendix F5 (WWIN cov. maps)	Main report: - Fig. 18, pg. 28 - Fig. 21, pg. 31 - Fig. 22, pg. 32 Appendix I, pg. 12 (WETA, WPOC, WNEW only)	Audio quality of host analog signal (recorded simultaneously with IBOC audio)	Digital coverage comparable to analog coverage along test radials. WWIN demonstrated good performance using low-power IBOC/analog combiner WNEW demonstrated good performance using centrally located urban facility, combined antenna Subjective: IBOC audio quality was equal to or better than analog for all audio cuts evaluated
Field – B.3 – System performance – 2nd adj. channel interference	Main report: - Fig. 4, pg. 14 (WNEW digital coverage vs. interferer) - Fig. 5, pg. 15 (KLLC digital coverage vs. interferer) - Fig. 6,7, pgs. 16, 17 (WHFS digital coverage vs. interferer) - Fig. 12, pg. 22 (WWIN digital coverage vs. interferers) Appendix F3 (WHFS cov. maps) Appendix F4 (WNEW cov. maps) Appendix F5 (WWIN cov. maps) Appendix F7 (KLLC cov. maps) Appendix F8 (WD2XAB cov. maps)	Main report: - Fig. 19, pg. 29 - Fig. 20, pg. 30 Appendix I: - Pg. 13 (single 2nd – KLLC, WD2XAB, WNEW only) - Pg. 14 (dual 2nd – WHFS only)	Audio quality of host analog signal (recorded simultaneously with IBOC audio)	Digital coverage comparable to analog coverage along test radials. Subjective: IBOC audio quality was equal to or better than analog for all audio cuts evaluated

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Field – high multipath (not in test procedure)	Main report: Appendix F6 (KWNR cov. maps) Appendix F7 (KLLC cov. maps)	Main report: - Fig. 21, pg. 31 - Fig. 22, pg. 32 Appendix I, pg. 16	Audio quality of host analog signal (recorded simultaneously with IBOC audio)	Subjective: IBOC audio quality rated consistently higher than analog
Field - various	n/a	Appendix K: - Fig. 1, pg. 2 - Figs. 2-9, pgs. 4-11 - Fig. 10, pg. 12	Impairments observed in automotive receivers	"Ticker test" - audio from analog receivers contained 4-5 times more impairment events (6-7 times the number of severe impairment events) than audio from IBOC receivers

As evident from the numerous entries in Table 11, the NRSC's test program contained a substantial number of tests pertaining to these criteria. This seems appropriate since service area and coverage are arguably the most important aspects of a broadcasting service, those which all other aspects build upon. In the sections that follow, test results and details on how service area and coverage are impacted by various types of interference will be given.

In general, these results demonstrate that the "digital" service area of a radio station broadcasting FM IBOC should be an improvement with respect to existing analog service, due primarily to FM IBOC's robustness in the presence of multipath fading. Farther out from the transmitter, as signal strength decreases, the FM IBOC receiver at some point blends to analog (the data suggests this typically occurs at signal levels of 45-50 dBuV/m) and consequently radio service on the edge of coverage will be preserved in its present form for stations broadcasting in hybrid FM IBOC mode. Where exactly blending occurs in these outer areas will depend on nearness to interferers, terrain between the receiver and the transmitter, etc.

4.5.1 With impulse noise

Impulse noise interference can occur in both mobile (*e.g.*, from ignition circuits in automobiles) and household (*e.g.*, from vacuum cleaner motors) environments, reducing the audio quality of radios. The NRSC subjected the iBiquity FM IBOC prototype receiver and the two analog automotive receivers to impulse noise interference at various repetition rates under laboratory conditions. Audio recordings were made under these circumstances and then subjectively evaluated, the results of which are shown in Figure 11.

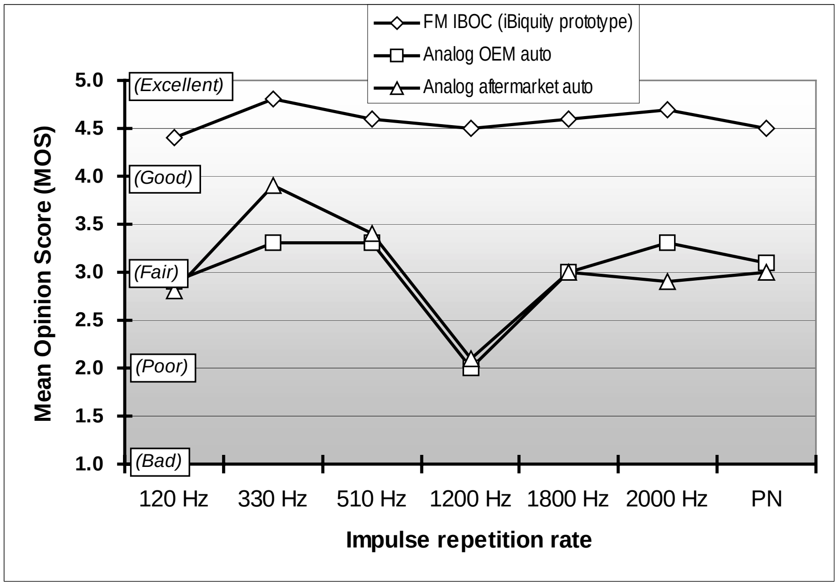

Figure 11. Comparison of FM IBOC and analog audio subjective evaluation results under laboratory impulse noise conditions

These results indicate that the FM IBOC receiver performs significantly better than the analog automotive radios for all impulse repetition rates tested. A second test, identical to the one just described except with the addition of an upper 1st-adjacent channel interferer (at +6 dB D/U) yielded similar results for repetition rates of 120 Hz and 330 Hz, however for the remaining repetition rates the FM IBOC receiver was either blending back and forth between digital and analog audio, or was blended to analog all together.

Overall these results demonstrate that FM IBOC is significantly more robust when subjected to impulse noise interference than is existing analog FM.

4.5.2 With co-channel interference

To determine the performance of the FM IBOC system in the presence of (FM IBOC) co-channel interference in the laboratory, a co-channel interferer was introduced and increased in power level until the desired FM IBOC signal blended to analog. In this manner it was established that a +2 dB D/U ratio was required to cause the desired signal to blend to analog.

After establishing the +2 dB blend point, the level of interference was reduced by 2 dB (resulting in a +4 dB D/U) and recordings of the FM IBOC receiver audio (now digital audio since the operating point had been "backed off" from where the system blends) and audio from the four analog receivers were made. Note that both the desired and undesired signals supplied to the analog receivers were FM analog (not hybrid IBOC), set for a D/U of +4 dB. Under these conditions, two of the analog receivers failed (OEM auto, home hi-fi); recordings from the remaining receivers were subjectively evaluated (Figure 12).

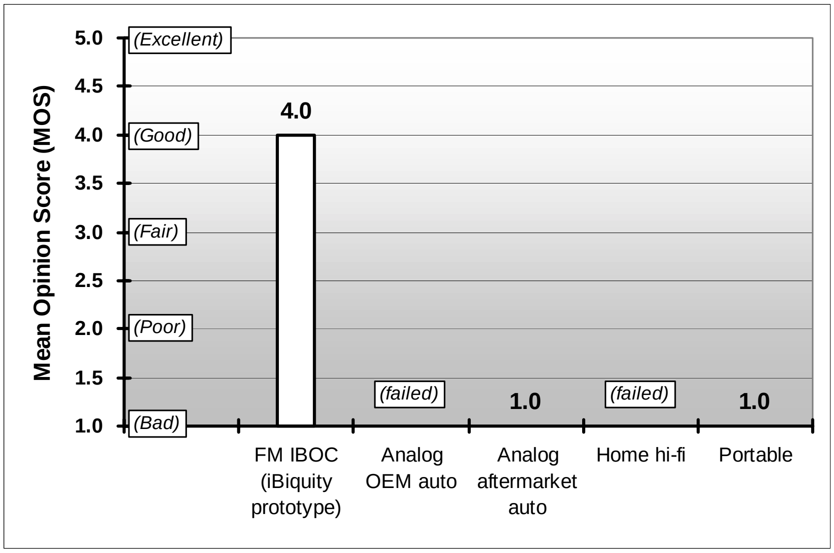

Figure 12. Comparison of FM IBOC and analog audio subjective evaluation results with co-channel interference (+4 dB D/U)

Additional laboratory tests were done using the four multipath scenarios called for in the test procedures (rural fast, terrain obstructed, urban fast, urban slow) and the results were essentially the same, with FM IBOC far outperforming analog FM.

These results demonstrate that FM IBOC is significantly more robust to co-channel interference than is existing analog FM. Amazingly, the FM IBOC receiver achieved "good" audio quality (at the +4 dB D/U operating point) while the analog receivers were either totally failed or exhibiting the lowest quality allowed on the MOS rating scale ("bad"). Note that this operating point is well beyond (by 16 dB) the value to which analog stations are currently protected from co-channel interference.

4.5.3 With 1st-adj. chan. interference

Extensive testing in both the laboratory and the field was conducted to determine the performance of the FM IBOC system in the presence of 1st-adjacent (hybrid FM IBOC) interference. This is an important case to consider because as a consequence of the system design, the digital sidebands of an FM IBOC signal are vulnerable to interference from a 1st-adjacent signal (as shown in Figure 2 above).

Subjective evaluation results from field test data collected on FM IBOC performance with a single 1st-adjacent channel is given in Figure 13. The graphs included in this figure compare the FM IBOC audio quality with that of the host analog signal (obtained simultaneously to insure that the RF signal conditions were the same for both the IBOC and analog audio). An inspection of these graphs indicates that the FM IBOC audio quality either equals or surpasses that of the host analog signal under 1st-adjacent channel interference conditions—note that while there are significant variations in the analog receiver quality, the IBOC receiver quality is consistently in the "good" to "excellent" range.

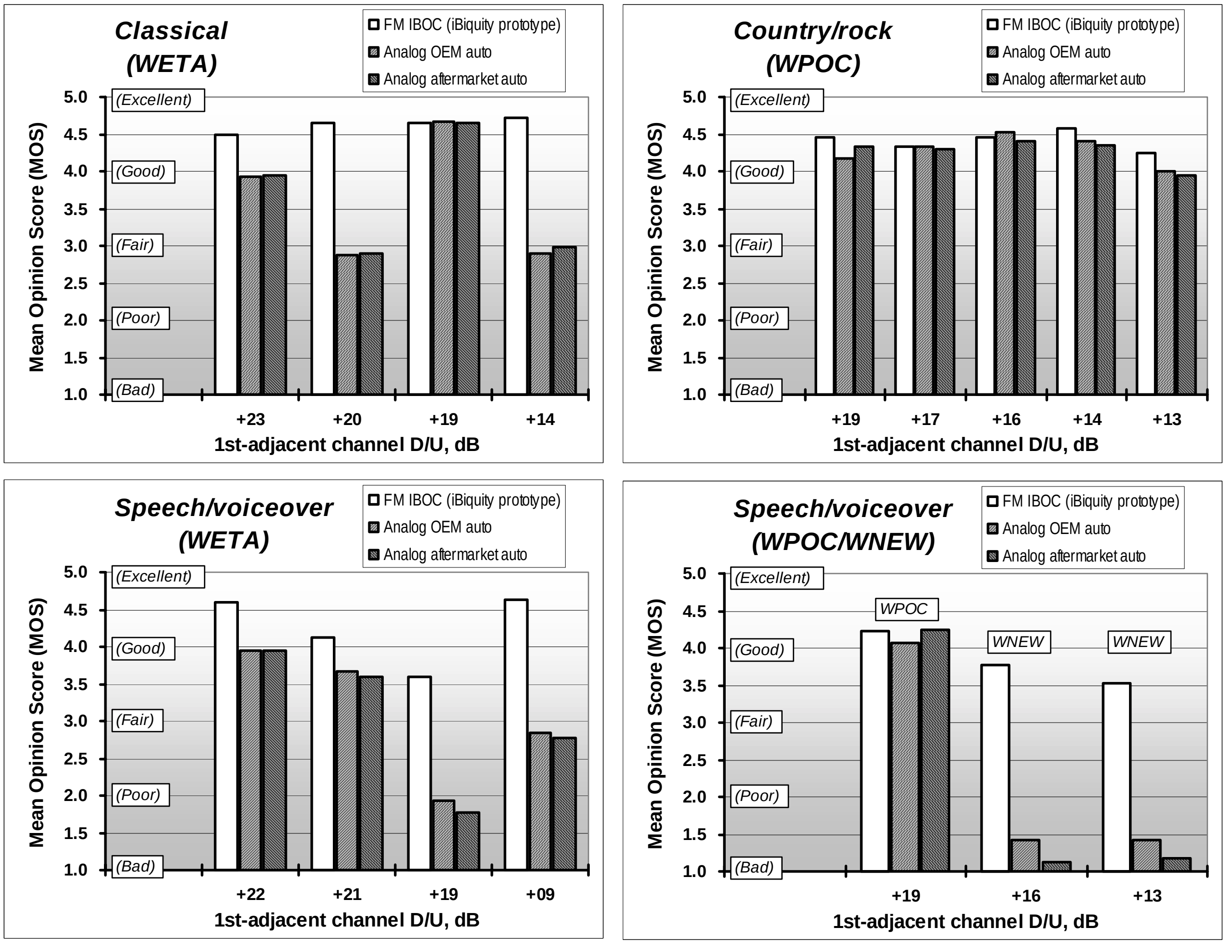

Figure 13. Comparison of FM IBOC and analog audio subjective evaluation results with 1st-adjacent channel interference

Tests were also done (in the laboratory) on digital performance in the presence of dual 1st-adjacent channel hybrid IBOC interferers, utilizing an upper 1st-adj. interferer at +6 dB D/U, and a lower 1st-adj. interferer whose power level was increased until the IBOC receiver started blending to analog. For this test, blending occurred when the lower 1st-adj. chan. interferer was at a D/U ratio of approximately +21 dB. This result is not surprising, since (as was mentioned in Section 3.1 above), at least one of the digital sideband groups is needed for generation of digital audio, and in the case of dual 1st-adjacent channel interference both IBOC sidebands groups are being interfered with, resulting in the need for the system to blend to analog.

4.5.4 With 2nd-adj. chan. interference

Laboratory tests of digital performance in the presence of single and dual 2nd-adjacent IBOC interferers established that the iBiquity FM IBOC system is extremely robust with respect to this type of interference, and confirms that the 4 kHz guard band between 2nd-adjacent IBOC digital sidebands (see Figure 3 and discussion in Section 3.1 above) is adequate. Specifically, even when the D/U ratio was set to the laboratory test bed limit of -42 dB (for single interferer) or to -42 dB (lower), -20 dB (upper) in the dual interferer case, the system did not experience any blending to analog.

In the field, results were obtained in the presence of a 2nd adjacent analog signal at a number of test sites. The 90º radial from field test site WNEW is a good illustration of this (Figure 14). This radial is on a direct line with the transmitter of WBAB, a lower 2nd adjacent channel station. As can be seen in the figure, digital coverage for WNEW extended to the 100 dBu contour of WBAB, at which point the IBOC receiver was experiencing a D/U ratio of approximately –47 dB (7 dB more severe than the FCC protection ratio for 2nd adjacent signals).

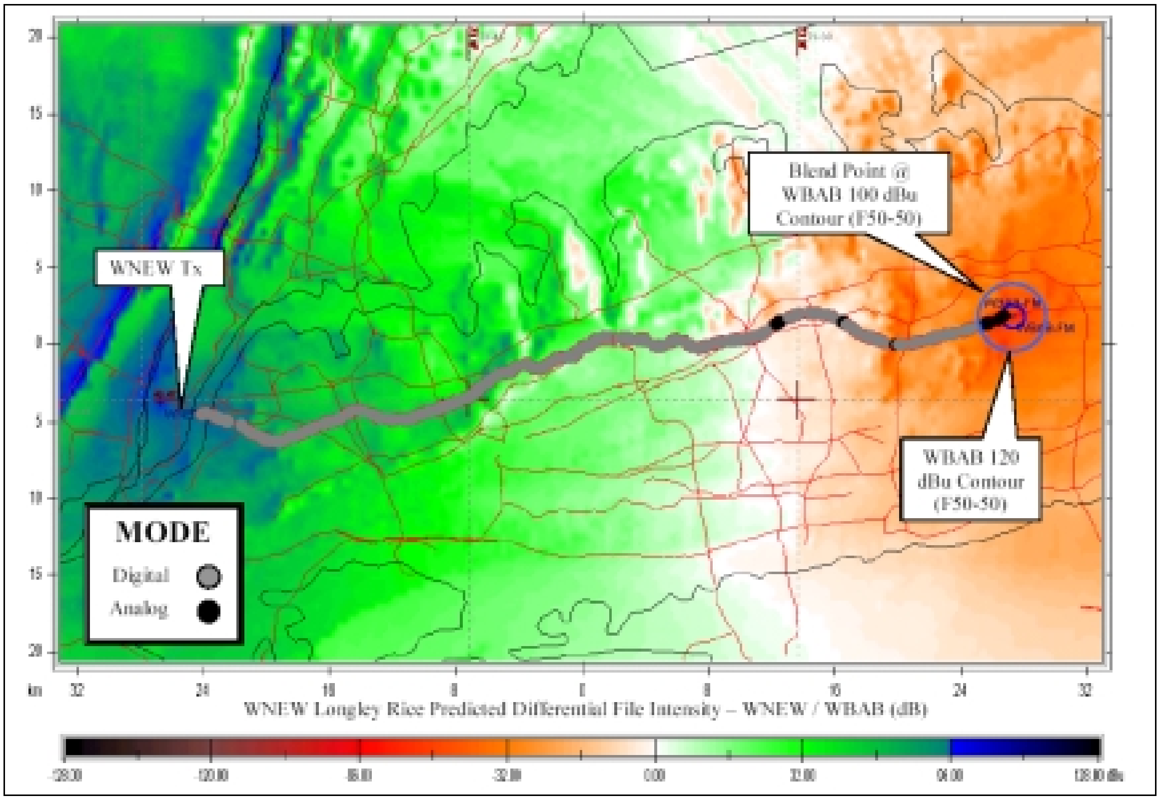

Figure 14. Field test radial illustrating 2nd-adjacent channel performance (WNEW, 90º radial)

4.5.5 With multipath

Of all the benefits provided listeners by IBOC technology, improved performance in the presence of multipath interference is likely to be the most profound. Laboratory and field testing indicates that compared to analog FM, FM IBOC is significantly more robust in the presence of multipath. A good example of this is shown in Figure 15, a digital coverage map obtained in Manhattan of an IBOC signal broadcast from WNEW, which indicates that the IBOC receiver operated without any blends to analog except in one location (related to passage through a tunnel) despite the high levels of multipath typical of Manhattan's urban canyons. Similar examples of robust urban performance exist from field tests performed in Las Vegas, NV, San Francisco, CA, and Washington, DC.

Figure 15. Map showing FM IBOC digital coverage along route in Manhattan, NYC.

In Figure 16, IBOC receiver performance is compared to analog automotive receiver performance in the laboratory when subjected to multipath interference, for four distinct types of multipath interference. In each case, the FM IBOC audio quality is good to excellent while under identical conditions, the analog audio quality ranges from poor to fair.

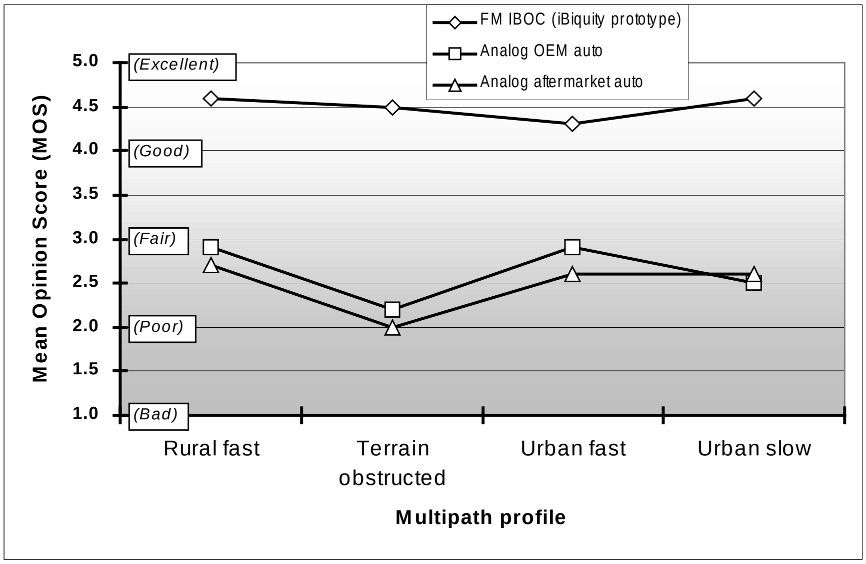

Figure 16. Comparison of FM IBOC and analog audio subjective evaluation results under laboratory multipath conditions

4.5.6 Versus broadcast antenna configuration and combining system

To test the performance and durability of iBiquity's IBOC system under different antenna and combiner configurations, field test stations were specifically selected to include a centrally-located urban antenna, a combined antenna, a low power IBOC combiner/common amplification system and a high power IBOC combiner system.

Most of the field test stations employed a high power combiner system to multiplex the analog and IBOC signals into the test station's existing antenna. The high power system uses separate transmitters for the IBOC and analog signals. The outputs of both transmitters are then combined using a 10-dB coupler. This type of combiner is a relatively simple four-port device consisting of two inputs, an output and dummy load connection. This type of combiner was utilized because of its simplicity and minimal impact on the analog operating power. However, since 90 percent of the IBOC energy input into the combiner is lost to the dummy load, higher IBOC transmitter output power is required to overcome the combining system losses.

WWIN, Glen Burnie, Maryland, employed a low power/common amplification system for multiplexing the IBOC and analog transmissions. In a low power/common amplification system the outputs of the IBOC and analog exciters are combined prior to amplification by a single transmitter. While the combining components employed in low power/common amplification system are considerably smaller, such an implementation requires the use of a transmitter employing a class A or class AB amplifier operation.

WNEW, New York, New York, utilizes a combined antenna in a centrally located urban environment. The Empire State Building master FM antenna, employed by WNEW, is shared with 12 other New York area stations. The WNEW IBOC operation was implemented by using a high power combining system prior to the master FM antenna combiner. No modifications nor tuning of the master FM antenna combiner were necessary to implement IBOC on WNEW.

In each case, no detrimental impact on IBOC performance or durability was observed due to the transmitting antenna or combining system employed. The maps and field strength graphs included as Appendix F of iBiquity's report demonstrate that IBOC performance results for WWIN and WNEW are comparable with other field test stations. The field tests on these different transmission systems serve to demonstrate the flexibility of the IBOC system.

4.5.7 Comparison of measured digital to predicted analog coverage

iBiquity submitted a series of maps depicting the predicted coverage of eight IBOC test stations[19] and the measured performance of each station's IBOC signal. This section of the EWG report contains a brief discussion of those maps as they pertain to comparing analog performance with digital performance within a station's coverage area.

For the iBiquity field test report submitted to the NRSC, audio samples and signal measurements were collected using receiving antennas that were placed relatively close to the ground, as would be the case with typical mobile, portable, and fixed receivers. Nominally, the receiving antenna height was approximately 2 meters (7 ft) above ground level. Signals were measured utilizing a calibrated spectrum analyzer connected to a calibrated sample feed from the antenna.

This signal strength information is depicted in a series of graphs submitted with the maps (Figure 17). Each field intensity graph presents the data collected on one radial drive test and contains field strength of the desired signal and of the upper and lower first adjacent channels, plus the digital-vs.-blend mode of the received digital and the distance from the transmitter. (Note that iBiquity utilized the signal strength information depicted in these graphs to tune the accuracy of the predictive signal strength maps it prepared for submission.)

[19] Stations represent a variety of terrain conditions, station classes and potential interference scenarios. See Table 4 in Section 3.3 above.

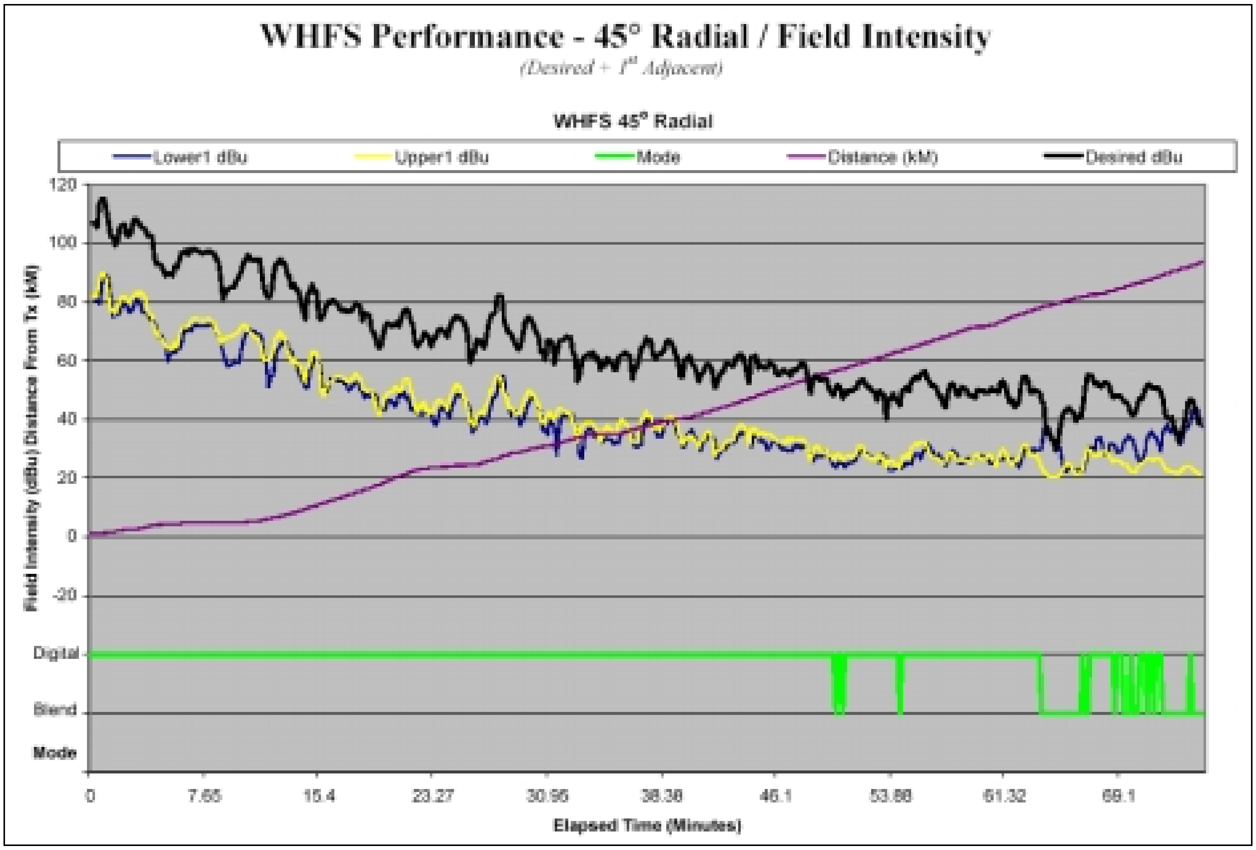

Figure 17. Field test signal strength graph (WHFS, 45º radial)

The test station coverage maps contained in the report each show two images overlaid to enable a comparison between predicted analog signal strength and actual digital IBOC reception (Figure 18; note that this map has been modified by the EWG as will be discussed below). The predicted signal strength information in these maps was generated with ComStudy software and appears as an underlay on each map. The underlay appears on the entire map as a continuum of regions of various colors. The continuum is formed by a matrix of colored pixels. Each pixel represents the predicted signal strength at the pixel's location on the map. The elevation at the location of each pixel is determined from the ComStudy digital elevation model, which has a three-second resolution. The signal strength at each pixel is predicted by employing the elevation data with ComStudy's Longley-Rice calculations. To simulate realistic reception conditions the propagation mode employs a receiving antenna height of 7 ft. (2 meter) above ground. On the transmitting side, the station's site, power, and antenna height above ground are entered in the computation.

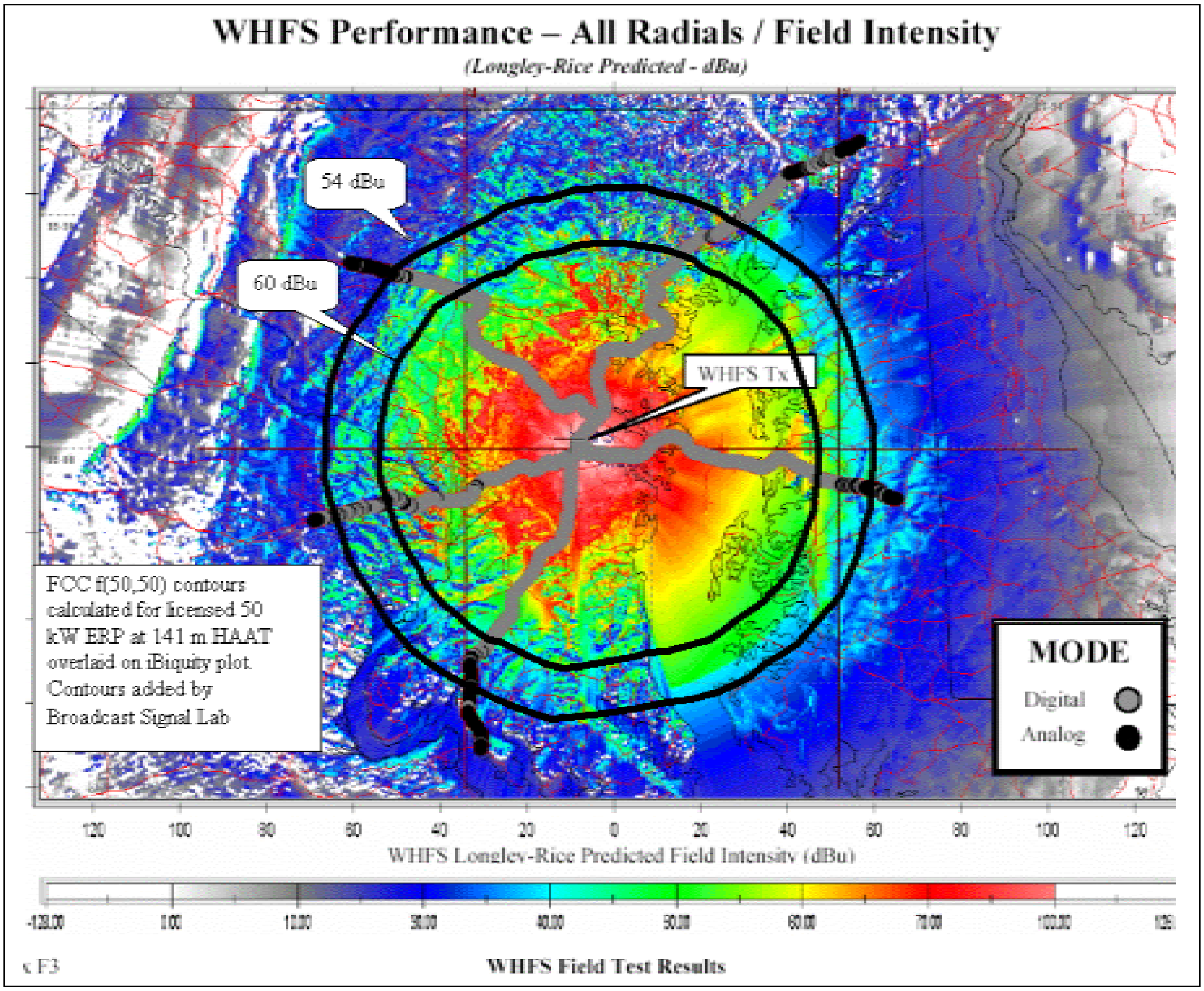

Figure 18. Coverage map including IBOC digital coverage (on radials), predicted field strength, and FCC 54 µV and 60 µV contour

The digital reception data are overlaid upon the propagation data and appear as sets of "worm trails" on the maps. The data were taken from mobile tests in which the test vehicle was driven on roads that generally radiate from the transmitter sites of the test stations. The data from which the worm trails were generated is presented on the signal strength graphs that accompany the maps. The worm trails indicate one of two conditions; either the digital signal was being received reliably (shown in gray), or the receiver had blended to analog (shown in black). No information was given to indicate what the quality of the blended-to-analog signal was. Hence, the digital reception radial drive test maps indicate positively where digital reception was reliable, but give no direct comparative information on the quality of the analog coverage of the station.

The iBiquity predicted signal strength underlays give a reasonably accurate picture of how the terrain affects reception of each radio station. They permit the map-reader to compare the predicted analog signal strength with digital performance.

The Evaluation Working Group found the iBiquity maps to be very helpful as a means of geographically comparing digital and analog performance of these IBOC stations. Because the signal strength predictions are based on actual terrain conditions and on typical receiving antenna heights, they do not depict official protected contours. The Evaluation Working Group chose to enhance these already insightful maps by adding predicted contours of 60 dBμ and 54 dBμ. An example of the results of these enhancements is shown on the map above (Figure 18).

These images permit the reader to compare the three relevant conditions for each station tested. Predicted strength of the analog signal is readily compared with both the FCC contours and the digital performance worm trails. The relationship between the digital performance and the FCC contours is also evident.

It is important to note the distinctions between the manner in which the FCC contours and the color signal strength matrix are computed. The color signal strength underlay is computer calculated based on receiving antenna heights of 2 meters and on actual terrain conditions (iBiquity employed field measurement data to adjust the accuracy of the color underlays to account for typical local land cover losses). In contrast, the official FCC F(50,50) contours represent the predicted signal strength at a receiving antenna 30 feet above ground and are based on simplified average terrain calculations.

While the iBiquity color underlays are more accurate representations of station signal strengths than the FCC contours, the inclusion of FCC contours brings the digital IBOC coverage data into the context of FCC interference protection criteria with which broadcasters are so familiar.

The stations presented in the maps illustrate the manner and the varying degrees to which terrain affects actual coverage. The common factor most apparent on the maps is how the digital IBOC signal remains uninterrupted on long traverses from the stations' transmitter sites to more distant locations. The locations where the digital IBOC signal blends to analog are generally indicated as locations where terrain and distance also impede the analog signal strength.

Typically, within a station's primary service area as defined approximately by its protected contour, the digital IBOC signal is extremely reliable wherever there is enough signal strength to support analog reception. When terrain obstructs analog signals significantly within the protected contour, there is no reason to expect the digital coverage to overcome the impact of the terrain obstruction.

At the points where the digital reception blends to the analog signal, the maps do not contain the kind of qualitative information necessary to determine analog performance. Analysis of the analog performance in the regions of blending is discussed in Section 4.8 below.

Similarly, the maps do not indicate locations where multipath conditions affect analog performance in areas of strong signal strengths. Comparison of analog and digital reception under these conditions is discussed in Section 4.5.5 above and in the "Ticker Test" Section 4.5.8 below.

Outside their protected contours it is commonly understood that stations may have some additional coverage that is limited by factors such as interference, terrain, and distance. The digital IBOC signals appear to provide coverage generally in areas where the analog signal strength is at useable levels. The stations may be subjected to interference from adjacent channels in some locations. The issue of co- and adjacent-channel interference to digital IBOC reception is addressed in Sections 4.5.2 through 4.5.4 of this report.

The eight maps submitted by iBiquity represent a variety of station classes, terrain conditions and interference scenarios (see Table 4 above). While these test stations provide a good cross section of various conditions, they of course represent a very small percentage of the FM stations in the U.S. and cannot be employed as the only means of verifying IBOC digital service area. The general association among the maps, between predicted analog signal strength and measured digital performance, does suggest that careful generalizations can be made about digital coverage area to the degree they are supported by lab test data. This data is discussed elsewhere in this Section.

In summary, the IBOC digital coverage maps supplied by iBiquity were verified by the EWG and enhanced with the inclusion of FCC contours. The iBiquity digital coverage maps illustrate how mobile digital reception along routes radiating from eight test stations is extremely reliable within the approximate service areas defined by the protected contours. Within these contours the digital signals do not provide coverage where terrain already prevents analog coverage. Outside the areas defined by the contours, digital reception remains functional where the host analog signals are predicted to be at useable levels. In marginal areas mobile reception may be impeded but careful placement of a fixed receiver may result in reliable digital service. The maps do not account for the possibility that digital service in some cases may be interference limited, so conclusions about interference-limited coverage is left to analysis of other tests.

4.5.8 "Ticker Test"

To amplify upon data taken in the radial drive tests, iBiquity created a "Ticker Test" in which subjects listened to long samples of recorded test audio and "ticked" audible impairments. iBiquity solicited subjects from the general public who met minimum criteria for listening acuity. The Ticker Test illustrates the differences between what could be considered "normal" mobile analog reception within the coverage area and simultaneous digital reception of the same program. Normal mobile reception typically contains multipath and other propagation and interference effects that can degrade the quality of the received analog signal.

The Ticker Test was conducted with a total of eight sets of audio samples taken from the radial drive tests of test stations WETA and WPOC. Each sample was taken beginning at about ten miles distance from the transmitter and lasted for about 5 minutes. Samples were recorded simultaneously from the IBOC receiver and two analog automotive receivers, an OEM model and an aftermarket model. Information about the test is detailed in Appendix K of the FM IBOC Test Data Report.

The subjects made a "tick" each time they heard a transient impairment to the audio to which they were listening. Ticks represent audible impairments, regardless of the cause. Broadcast production errors would likely be common to all receivers tested, while multipath-induced artifacts or audio processing artifacts may be associated specifically with analog or digital reception or with a particular radio.

The total number of ticks earned by each receiver was tabulated for each of eight test recordings. The Delphi and Pioneer automotive radios earned an average of 844 and 1010 ticks respectively per test recording. The FM IBOC average was 180 ticks per test recording (see Figure 8 above).

iBiquity also subjectively tested audio samples from the audio of each Ticker Test. Subjects indicated a consistent preference for the IBOC audio under these typical mobile reception conditions. During the original Ticker Test listeners were able to "tick" a temporal impairment as either moderate or severe. The subjective tests involved audio samples that contained either moderate or severe ticks. With moderate impairments the automobile radios scored in the low "fair to good" range, between 3.0 and 3.5 MOS, under three kinds of programming—classical, country, or speech. The same samples of the IBOC audio scored in the low "good to excellent" range, between 4 and 4.5 MOS. The automobile radio audio samples of severe tick ratings yielded middle "poor to fair" results, around 2.5 MOS. During the periods of severe impairments to analog auto radio reception, the FM IBOC scored consistently "good" at about 4.2 MOS.

The subjective tests of the Ticker Test audio confirm that not only are the audible temporal impairments in mobile reception fewer in number with IBOC than analog, but also that the IBOC audio retains perceived high quality when analog reception is severely degraded.

The EWG found the Ticker Test results to be an impressive demonstration of IBOC's durability under multipath and related signal impairments. The mobile receivers presented about five times the number of audible impairments heard on the IBOC receiver. Listeners preferred the sound of the IBOC radio under the test conditions. Taken by itself, the Ticker Test is not scientifically conclusive. However, the Ticker Test results provide a clear confirmation of other observations in this report that mobile reception of the IBOC digital signal is significantly more immune to audible transient impairments within a station's primary coverage area than is the host analog signal.

4.5.9 Findings – service area

NRSC test results indicate that hybrid FM IBOC digital coverage is comparable to analog coverage along radial and loop routes tested. Due to FM IBOC's improved resistance to various types of interference (co- and adjacent channel, impulse noise, and multipath fading in particular), FM IBOC service may be available in areas where analog service is currently of unacceptable quality due to such interference.

4.5.10 Findings – durability

NRSC test results demonstrate that the iBiquity hybrid FM IBOC system, compared to analog FM, is substantially more robust under impulse noise, co- and adjacent channel interference, and multipath fading conditions.

4.6 Criterion 4 – Acquisition performance

Table 12 lists the test result pertaining to acquisition performance of the iBiquity FM IBOC system.

Table 12. FM IBOC test results pertaining to acquisition performance

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Lab – H.1 – IBOC acquisition	Appendix D: - Table 33, pg. 64	n/a	Acquisition time of analog receiver	IBOC receiver acquisition time – 135 msec; mode - analog

The iBiquity FM IBOC system is designed such that an IBOC receiver will initially acquire an FM channel utilizing the analog portion of the hybrid FM IBOC signal. Once the digital portion of the signal is fully acquired (takes a few seconds), the receiver will then blend from analog audio to digital audio. Consequently, an IBOC receiver has the same acquisition performance as does an analog radio. This was confirmed by NRSC lab test H.1, where the acquisition time was measured to be 135 msec.

4.6.1 Findings

The acquisition performance of the iBiquity hybrid FM IBOC system is identical to that of an analog FM radio since, by design, an IBOC receiver initially acquires the analog portion of the hybrid FM IBOC signal.

4.7 Criterion 5 – Auxiliary data capacity

According to the system specification, the iBiquity FM IBOC system operating in hybrid mode supports transmission of an auxiliary data stream along with the main channel audio data stream with a capacity as shown in Table 13.[20] This system feature was not tested by the NRSC.

Note that the actual capacity supported is inversely related to the main channel audio bit rate such that the sum of the main channel digital audio bit rate and the auxiliary data rate equals 99-100 kbps, with the variability indicated here being due to the fact that part of this capacity is "opportunistic" in nature, depending upon the operation of the perceptual audio codec. The minimum dedicated portion (i.e. non-opportunistic) of the auxiliary data capacity is 1 kbps, and can be increased in 8 kbps increments with a corresponding decrease in the main channel digital audio data rate.

Table 13. Auxiliary data capacity of the iBiquity FM IBOC system - data rates include 2-3 kbps average rate for opportunistic data[21]

Operating mode	With 96 kbps main channel audio	With 64 kbps main channel audio
Hybrid	3-4 kbps	35-36 kbps

4.7.1 Findings

The iBiquity hybrid FM IBOC system design incorporates an auxiliary data transmission feature with a minimum capacity of 3-4 kbps. This system feature was not tested by the NRSC.

4.8 Criterion 6 – Behavior as signal degrades

This criterion pertains to how an IBOC receiver generally behaves as the received signal becomes weak (due to blockage or distance from the transmitter), or encounters severe degradation due to interference (*e.g.*, multipath fading) compared to how an analog receiver would behave under similar conditions. Table 14 lists the test results pertaining to behavior as signal degrades of the iBiquity FM IBOC system.

[20] See FM IBOC Test Data Report, Appendix A.
[21] See FM IBOC Test Data Report, main report, pg. 35, Section E, and Appendix A.

Table 14. FM IBOC test results pertaining to behavior as signal degrades

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	ANALOG BENCHMARK	RESULTS / COMMENTS
Field – Performance at blend (NRSC procedures as amended by Steering Committee)	n/a	Main report: - Fig. 25, pg. 38 Appendix I, pg. 15	Audio quality of host analog signal (recorded simultaneously with IBOC audio)	IBOC audio cuts containing blends (to analog) were tested Subjective results: Audio quality of IBOC with blends nearly identical to corresponding analog

Fundamentally, by virtue of the FM IBOC system's blend to analog feature, an FM IBOC receiver behaves similar to an analog receiver as the signal weakens or otherwise approaches the outer limits of a reception area. This behavior differs from that of other digital broadcast systems which, under similar conditions, exhibit the so-called "cliff effect," whereby the signal transitions from a high-quality digital signal to muting. iBiquity has indicated to the NRSC that the "blend point" of the system has been placed such that blending to analog will occur prior to the point where the received digital audio would start experiencing undesirable, audible artifacts ("clicks," "pops," etc.) due to signal degradation. According to iBiquity, this point is established by monitoring the block error rate (BLER, which increases with increasing signal degradation) as well as the overall error statistics, and blending is initiated at a BLER of approximately 10% (meaning that 10% of the received data blocks have one or more un-correctable errors).

As part of the NRSC evaluation, audio recordings were obtained in the field at the point where the FM IBOC receiver was blending between analog and digital such that the blend process was captured; consequently, this audio is a combination of digital, analog, and the blending between the two. These recordings were then compared subjectively to recordings made on analog automotive receivers at the same time under the same conditions and the results of these evaluations are shown in Figure 19. These results demonstrate both that the FM IBOC audio during the blend process is perceived to have the same quality as does the analog audio, and, that the blend process itself does not degrade the audio quality below that of analog.

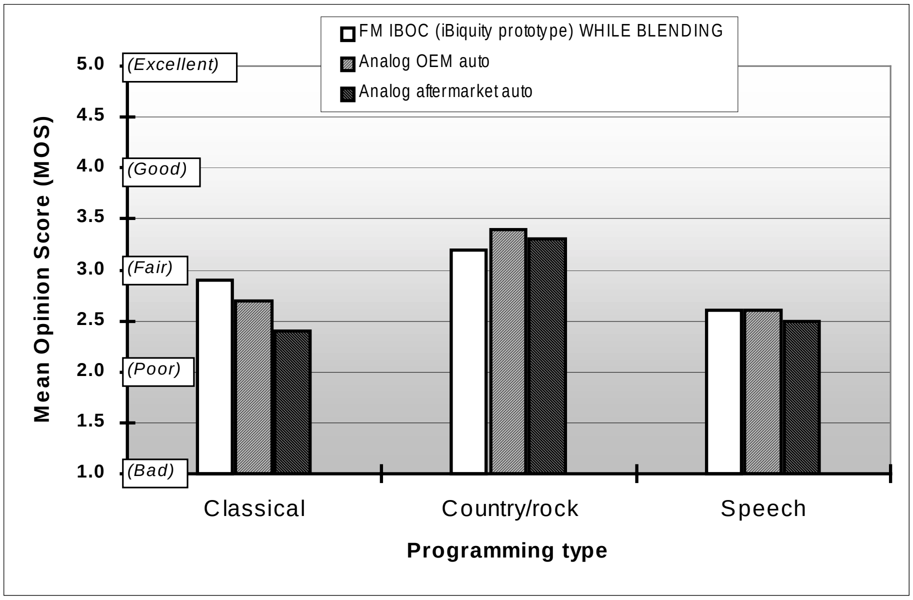

Figure 19. Comparison of FM IBOC and analog audio subjective evaluation results at "blend to analog" operating point

4.8.1 Findings

NRSC testing has demonstrated that the iBiquity prototype hybrid FM IBOC receiver's audio during the blend process is perceived to have the same quality as does the analog audio, and, that the blend process itself does not degrade the IBOC receiver's audio quality below that of analog.

4.9 Criterion 7 – Stereo separation

Unlike the blend to monophonic mode used by the FM automobile radio manufacturers (discussed in Appendix G to this report), the hybrid FM IBOC receiver tested by the NRSC remains in full stereo as long as digital audio is available. Under certain signal conditions (as discussed in Section 3.1 above) the IBOC receiver output blends to analog. Since (as discussed in Appendix G) analog automotive FM receivers blend to mono under a variety of circumstance for which an IBOC receiver (under the same conditions) should still be receiving digital stereo audio, the FM IBOC receiver should exhibit superior stereo separation compared to analog automotive FM receivers.

4.9.1 Findings

FM IBOC receivers are expected to exhibit superior stereo separation compared to analog automotive FM receivers due to the fact that the FM IBOC receiver should be receiving digital stereo audio under circumstances for which an analog automotive FM receiver would be blending to mono.

4.10 Criterion 8 – Flexibility

Appendix A of the FM IBOC Test Data Report, the "IBOC FM Transmission Specification," documents a number of features of the FM IBOC system which should provide significant flexibility for both broadcasters and receiver manufacturers, including:

- Modes of operation: three modes of operation are described—hybrid mode, extended hybrid mode, and all-digital mode—offering significant opportunities for individualizing the broadcast signal to specific needs and for future improvements in system performance. Only the hybrid mode has been tested by the NRSC.

- Audio coding rate: the bit rate used for transmission of the main channel audio signal can be varied, allowing for re-allocation of the digital payload based on a broadcaster's particular requirements. NRSC testing of the FM IBOC system was done with the audio coding rate fixed at 96 kbps (the maximum rate supported in the hybrid mode of operation).

- Auxiliary data rate: (this is discussed in Section 4.7 above in greater detail) the FM IBOC system supports transmission of an auxiliary data stream along with the main channel audio bit stream. The actual amount of auxiliary data transmitted can be decreased or increased in conjunction with a corresponding increase or decrease in the audio coding rate. This system feature was not tested by the NRSC.

- On-channel repeaters: the use of OFDM modulation in the FM IBOC system allows on-channel digital repeaters to fill areas of desired coverage where signal losses due to terrain and/or shadowing are severe. This system feature was not tested by the NRSC.

4.10.1 Findings

There are a significant number of features in the iBiquity FM IBOC system which should provide for system flexibility and should offer broadcasters and receiver manufacturers opportunities to customize services and equipment for their particular goals, and offer the possibility of performance improvements in the future. None of these features were tested by the NRSC.

4.11 Criterion 9 – Host analog signal impact

Table 15 lists the test results submitted pertaining to host analog signal impact of the iBiquity FM IBOC system.

Table 15. FM IBOC test results pertaining to host analog signal impact

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	RESULTS / COMMENTS
Lab – J.1, J.2 - IBOC ➜ host analog (main channel audio)	Appendix D: - Table 5, pg. 15 (Delphi) - Table 6, pg. 15 (Pioneer) - Table 7, pg. 15 (Technics) - Table 8, pg. 16 (Sony)	Appendix D: - Table 11, pg. 22 Appendix I, pg. 28	Objective: Delphi, Pioneer: results with IBOC and analog interferers nearly identical; Technics: IBOC interferer degraded S/N ratio 6-9 dB Sony: IBOC interferer degraded S/N ratio approx. 15 dB Subjective: results with and without IBOC nearly identical
Lab – J.3 - IBOC ➜ host analog (FM subcarriers-spectral plots)	Appendix SCA-A: - Table 9, pg. 22 - Figs. 1-16, pgs. 23-38 (spectral plots with and without IBOC)	n/a	Noise floor in subcarrier region of FM baseband increases with: - addition of IBOC sidebands - addition of main channel audio modulation - addition of RF noise - reduction in RF input signal level
Lab – J.4 - IBOC ➜ host analog (analog FM subcarrier audio quality)	Appendix SCA-A: - Table 10, pg. 39 (67 kHz, McMartin-before repair) - Table 11, pg. 40 (67 kHz, McMartin- after repair) - Table 12, pg. 40 (67 kHz, Norver) - Table 13, pg. 40 (92 kHz, CozmoCom) - Table 14, pg. 41 (92 kHz ComPol)	Appendix SCA-A: - Table 18, pg. 53 Appendix SCA-C, pg. 1	Objective: 67 kHz: McMartin receiver audio S/N reduced 3-8 dB when IBOC present; Norver, 6-12 dB 92 kHz: CozmoCom receiver audio S/N reduced 6-7 dB when IBOC present; ComPol fails (audio S/N reduced to 8-9 dB when IBOC present). Subjective: 67 kHz: McMartin audio quality nearly identical when IBOC present; Norver audio quality reduced from good to fair. 92 kHz: CozmoCom audio quality reduced from poor to bad when IBOC present; ComPol from fair to bad.
Lab – J.5, J.6 - IBOC ➜ host analog (RDS, DARC subcarrier performance)	Appendix SCA-A: - Table 15, pg. 42 (RDS) - Table 16, pg. 43 (DARC)	n/a	Results with and without IBOC identical for both RDS and DARC (in all cases, BLER after correction equals 0)
Field – C.1 – host compatibility (main channel audio)	Appendix F9: - Pg. 1 (WETA locations) - Pg. 2 (WPOC locations)	Main report: - Fig. 26, pg. 40 Appendix I, pg. 17	Results with and without IBOC nearly identical for all 4 analog receivers tested
Field – C.2 – host compatibility (FM subcarriers)	Appendix SCA-B: - Pg. 1 (WPOC locations – 67, 92 kHz analog subcarriers) - Pg. 2 (WPOC locations – RDS digital subcarrier) - Pg. 3 (WD2XAB locations – 67, 92 kHz analog, DARC digital subcarriers) - Pg. 4 (Table – field test strength by test and location) Appendix SCA-D: - Pg. 1 (Table – RDS BLER) - Pg. 2 (Table – DARC BLER)	Appendix SCA-C, pg. 6	Digital subcarriers: Results with IBOC and analog interferers identical for RDS, nearly identical for DARC.

The FM band IBOC digital radio system transmits the digital signals in the first half of the upper and lower host first adjacent channels (see Figure 1 above). The signals are transmitted in two frequency bands that extend from 129 kHz to 198 kHz above and below the host FM channel center frequency. The average total power of the two IBOC digital signals is 20dB below the host FM signal (-20dBc).

Consumer radios have used several methods for decoding the FM stereo difference signal. In practice the PLL stereo decoder has become the norm. The PLL stereo decoder uses square wave switching to decode the 38 kHz stereo difference signal. This decoder is sensitive to signals that are at odd multiples of 38 kHz. Without the addition of filters or special circuitry to the PLL stereo decoder, the IBOC digital signal that is transmitted at 190 kHz (five times 38 kHz) above and below the FM channel center frequency will increase the stereo audio noise floor. Most automobile radios use PLL stereo decoders that are not sensitive to the host IBOC signal. Monophonic radios are not affected by the host IBOC digital signal.

4.11.1 Host compatibility tests

Objective laboratory tests were conducted by the ATTC at strong signal levels with and without 30,000K AWGN. WQP S/N measurements were made with and without the IBOC signal added to the analog. Laboratory objective stereo separation tests were also conducted with less than 1dB separation change with and without the IBOC signal.

The addition of the digital signal caused no measurable change in the host analog S/N performance for the automobile radios, Table 16. The home hi fi radio S/N is reduced to 49dB WQP with the IBOC. The portable radio S/N was reduced to 35dB WQP with IBOC (WQP S/N is typically 10dB lower than RMS).

Table 16. Host compatibility objective laboratory test results at –47 dBm (strong) signal level

RADIO	TYPE	FM ONLY WQP S/N (DB)	IBOC WQP S/N (DB)	FM+AWGN WQP S/N (DB)	IBOC+AWGN WQP S/N (DB)
Delphi	Auto	59	59	56	56
Pioneer	Auto	56	56	54	54
Technics	Home hi fi	59	49	55	49
Sony	Portable/Bookshelf	51	35	49	35

4.11.2 Range of FM stereo hi fi and portable radio sensitivity to the host IBOC signal

Previous receiver laboratory tests conducted by CEA measured the sensitivity to host digital signals on 15 FM stereo radios. Five of the radios tested were automobile, one top-of-the-line tuner, and the remaining nine were home hi fi and portable. These tests were conducted using a simulated IBOC signal, with the digital signal operating at –22 dBc, 2dB lower than the present level. The 2dB lower IBOC level should not make a difference in establishing a range of FM stereo radio S/N performance with IBOC.

Table 17 lists the nine hi fi and portable radios tested by CEA and shows the difference in S/N performance caused by the addition of the IBOC signal, in descending order. Radios 1 and 8 are of the same make and almost identical radios to those used for the IBOC laboratory and field tests. The changes in the newer models were more cosmetic than electronic.

Table 17 shows that the Technics hi-fi (no. 1) and the Sony table/portable (no. 8) radios, the type used for the IBOC laboratory and field tests, are at the high and low ends for the range of the S/N performance.

Table 17. Simulated IBOC to host FM stereo performance range table (hi-fi and portable receivers)

NO.	MAKE	TYPE	PREDICTED S/N RANGE (RMS, DB)
1	**Technics**	**hi fi**	**Reference**
2	Denon	hi fi	0
3	Sony	Personal Portable	–3
4	Sony	hi fi	–4
5	Magnavox	Table/Portable	–4
6	Panasonic	Portable	–7
7	Pioneer	hi fi	-10
8	**Sony**	**Table/Portable combo**	**–11**
9	Sanyo	Shelf combo	-12

4.11.3 Laboratory subjective tests

Audio recordings were made with three types of processed program material: classical, rock, and speech. The subjective tests were conducted at a separate specialized audio subjective evaluation laboratory. Using the MOS rating on a scale of five, the Delphi radio deviated no more than 0.1 MOS units with any combination of FM, IBOC, or AWGN. The Pioneer with AWGN showed a decrease in performance of 0.4 from the analog for both classical and speech. There was no change in S/N or stereo separation for this test. The Sony radio S/N changed from 51dB to 35dB with IBOC, and the subjective performance changed from 2.9 without IBOC to 3.1 with IBOC.

4.11.4 Field subjective tests

Only subjective host compatibility tests were conducted. The tests were conducted at fixed sites. Three types of off-air program material were selected: classical, country/rock, and speech. For the classical and country/rock the largest deviation with IBOC for all four radios was 0.2 MOS. For the speech transmissions the largest deviation with IBOC was 0.3 MOS for all four radios. See Figure 9 above for graphs showing host compatibility subjective evaluation results.

4.11.5 Findings

NRSC tests indicate that listeners should not perceive an impact on analog host reception due to hybrid FM IBOC operation.

4.12 Criterion 10 - Non-host analog signal impact

In this section, the compatibility of an IBOC signal with co- and adjacent-channel analog signals will be considered. Table 18 describes where the test results pertaining to the non-host analog signal impact of the iBiquity FM IBOC system may be found in the FM IBOC Test Data Report, and provides some brief comments about these results. A more detailed analysis is provided in the paragraphs that follow.

Table 18. FM IBOC test results pertaining to non-host analog signal impact

TEST NO. (PROCEDURES)	OBJECTIVE DATA	SUBJECTIVE DATA	RESULTS / COMMENTS
Lab – F.1, F.3 - IBOC ➜ analog (main channel audio), single 1st adj.	Appendix D: - Table 1, pg. 7(Delphi) - Table 2, pg. 9 (Pioneer) - Table 3, pg. 11 (Technics) - Table 4, pg. 13 (Sony)	Appendix D: - Table 9, pg. 18 Appendix I, pg. 29-31	Objective: Delphi: IBOC interferer degraded performance at +6, -4, -14 dB D/U, performance with analog severely degraded at -24 dB D/U so IBOC impact not meaningful; Pioneer: IBOC interferer degraded performance at +6 and -4 dB D/U, performance with analog severely degraded at -14 and -24 dB D/U so IBOC impact not meaningful; Technics: performance with analog severely degraded at +6, -4, -14 and –24 dB D/U so IBOC impact not meaningful; Sony: performance with analog severely degraded at +16, +6, -4, -14 and –24 dB D/U so IBOC impact not meaningful; Subjective: Delphi, Pioneer, Technics: IBOC interferer degraded performance at +6 and –4 dB D/U, impact most significant for speech programming; Sony: results with IBOC and analog interferers nearly identical
Lab – F.2, F.4 - IBOC ➜ analog (main channel audio), single 2nd adj.	Appendix D: - Table 1, pg. 7(Delphi) - Table 2, pg. 9 (Pioneer) - Table 3, pg. 11 (Technics) - Table 4, pg. 13 (Sony)	Main report: - Fig. 36, pg. 54 - Fig. 37, pg. 55 Appendix D: - Table 9, pg. 18 Appendix I, pg. 32-33	Objective: Delphi, Pioneer: results with IBOC and analog interferers nearly identical; Technics: IBOC interferer degraded performance at -30, -35, -40 dB D/U; Sony: performance with analog sufficiently degraded that IBOC impact not meaningful Subjective: results with IBOC and analog interferers nearly identical
Lab – F/SC.1, F/SC.5 - IBOC ➜ analog (analog FM subcarriers), single 1st adj.	Appendix SCA-A: - Table 2, pg. 8 (67 kHz, McMartin- before repair) - Table 3, pg. 10 (67 kHz, McMartin- after repair) - Table 4, pg. 12 (67 kHz, Norver) - Table 5, pg. 14 (92 kHz, CozmoCom) - Table 6, pg. 16 (92 kHz ComPol)	Appendix SCA-A: - Table 17, pg. 45 Appendix SCA-C, pg. 2	Objective: 67 kHz: results with IBOC and analog interferers nearly identical; 92 kHz: slight impact with CozmoCom (1.5-4 dB) due to IBOC interferer in +16 dB D/U case (no noise); this impact masked by 30,000K noise. Subjective: 67 kHz: audio quality reduced when IBOC interferer present (*e.g.*, fair to poor); 92 kHz: audio quality bad to poor with or without IBOC.

Lab – F/SC.2, F/SC.6 - IBOC ➜ analog (analog FM subcarriers), single 2nd adj.	Appendix SCA-A: - Table 2, pg. 8 (67 kHz, McMartin- before repair) - Table 3, pg. 10 (67 kHz, McMartin- after repair) - Table 4, pg. 12 (67 kHz, Norver) - Table 5, pg. 14 (92 kHz, CozmoCom) - Table 6, pg. 16 (92 kHz ComPol)	Appendix SCA-A: - Table 17, pg. 45 Appendix SCA-C, pg. 3	Objective: 67 kHz: McMartin receiver fails with IBOC interferer at –30 dB D/U; Norver receiver fails with both IBOC, analog interferers at -20 dB D/U 92 kHz: CozmoCom receiver S/N reduced 3-15 dB by IBOC interferer at -20 dB D/U; ComPol reduced 14-21 dB by IBOC interferer at -20 dB D/U. Subjective: 67 kHz: McMartin audio quality goes from fair to bad when IBOC interferer present for -30 dB D/U; 92 kHz: receivers fail with IBOC interferer at -30 dB D/U but audio quality was bad to poor with analog interferer.
Lab – F/SC.3 - IBOC ➜ analog (digital FM subcarriers), single 1st adj.	Appendix SCA-A: - Table 7, pg. 18 (RDS) - Table 8, pg. 20 (DARC)	n/a	Results with IBOC and analog interferers identical for RDS, nearly identical for DARC.
Lab – F/SC.4 - IBOC ➜ analog (digital FM subcarriers), single 2nd adj.	Appendix SCA-A: - Table 7, pg. 18 (RDS) - Table 8, pg. 20 (DARC)	n/a	Results with IBOC and analog interferers identical for RDS, nearly identical for DARC.
Lab – G.1 - IBOC ➜ analog (main channel audio) with multipath, single 1st adj.	n/a	Appendix D: - Table 10, pg. 21 Appendix I, pg. 32-33	Subjective: Delphi, Pioneer: IBOC interferer degraded performance at +6 dB D/U, impact most significant for speech programming; Technics, Sony: n/a (mobile receivers only)
Field – C.3 – 1st adjacent compatibility	Appendix F9: - Pg. 3 (WETA locations) - Pg. 4 (WETA differential field intensity map) - Pg. 5 (WPOC locations) - Pg. 6 (WPOC differential field intensity map) - Pg. 7 (WNEW locations) - Pg. 8 (WNEW differential field intensity map)	Main report: - Fig. 27, pg. 42 - Fig. 28, pg. 43 - Fig. 29, pg. 44 - Fig. 30, pg. 45 - Table 7, pgs. 49-50 - Fig. 34, pg. 51 - Fig. 35, pg. 52 Appendix I: - Pg. 18 - Pg. 20 (with multipath) Appendix N	Objective: Longley-Rice predicted maps suggest only scattered small spots of IBOC impact in areas where good analog reception should now be possible. Subjective: Delphi, Sony: IBOC interferer degraded analog audio quality across all programming formats to some degree, but not to point that at least half of listeners would tune away; Pioneer, Technics: IBOC interferer degraded analog audio quality across all programming formats to some degree, but with the exception of speech programming not to the point that at least half of listeners would tune away; iBiquity reports no complaints from anyone (listeners, broadcasters, etc.) about degraded analog audio quality throughout entire field test program.

The data from the NRSC's FM IBOC compatibility tests seems to indicate that listeners were more critical of interference at a particular D/U ratio when the results came from the laboratory than when they came from the field. Additional information on this is provided in Appendix H of this report.

4.12.1 Co-channel compatibility

Introduction of hybrid FM IBOC should not add additional co-channel interference into the FM band. This is due to the fact that the power level of the analog portion of an interfering IBOC signal is 20 dB greater than that in the IBOC digital sidebands, and also to the fact that the analog portion of the interferer is frequency coincident with the analog portion of the desired signal, while the IBOC digital sidebands are in effect adjacent to the analog portion of the desired signal. Because this performance is dictated by design, the NRSC test procedures do not include tests for co-channel compatibility.

4.12.2 1st-adjacent channel compatibility

The digital sidebands in iBiquity's FM IBOC system occupy a portion of the spectrum used by the analog signals of the two first adjacent channel stations (as illustrated in Figure 2 above). That is, one of the digital sidebands for a particular FM IBOC station occupies a portion of the same spectrum used by an analog signal that is one channel below it, and the other digital sideband for the IBOC station occupies a part of the same spectrum used by the analog station that is one channel above it. As a result, first adjacent channel compatibility is one of the more significant challenges for the FM-band IBOC system.

In order to control first adjacent channel interference in the all-analog environment today, the FCC will only permit a new or modified FM station to go on the air if the new station will produce a signal at least 6 dB weaker than the signal of any nearby first adjacent channel station at the protected contour of the nearby first adjacent channel.

When analyzing the compatibility data that was collected during the NRSC's FM IBOC test program, a basic distinction was made between FM IBOC's impact inside the protected contours of existing analog stations versus its impact outside these protected contours, with the NRSC electing to focus on the area inside the protected contour. The NRSC is cognizant, however, that FM IBOC will potentially have an impact on analog listening beyond the protected contour, and for the broadcasters, receiver manufacturers and listeners to whom this is important an analysis of this impact is also provided.

4.12.2.1 1st-adjacent channel compatibility – inside the protected contour

The test program measured the performance of analog receivers when subjected to first adjacent channel FM IBOC signals at specific desired-to-undesired signal (D/U) ratios. Laboratory measurements were taken at 10 dB D/U intervals from +16 dB D/U to -24 dB D/U. Field measurements were taken at various D/U ratios from +6 dB D/U to -14 dB D/U. This test method allows the D/U ratio at which the FM IBOC signal will interfere with first adjacent channel analog reception to be identified within a specific range of D/U values for each test condition.

Included in the FM Test Data Report are the results of a subjective listening experiment in which typical radio listeners rated the audio quality of various audio segments, and also indicated whether or not they would continue listening to a station with that level of audio quality.[22] The results of this experiment provide the point, in terms of audio quality defined by an absolute quality rating mean opinion score (ACR-MOS) ranging from one to five, at which half the listeners stopped listening to a station for three types of programming (classical, rock and speech). Instead of five integer numbers, the listeners were asked to choose from among five adjectives (excellent, good, fair, poor and bad) when rating the audio. When converted to numerical values for analysis these adjectives were assigned the values five, four, three, two and one, respectively. The ACR-MOS scores where half the listeners stopped listening to the three types of program material are presented in Table 19.

[22] FM IBOC Test Data Report, Appendix J.

Table 19: Tune-out point for different types of programming

TYPE OF PROGRAMMING	AUDIO QUALITY AT AND BELOW WHICH HALF OF LISTENERS WOULD NOT LISTEN (ACR-MOS SCORE)
Classical	2.1
Rock	2.0
Speech	2.3

In addition to subjective ratings for audio samples from both the laboratory and the field, objective measurements of audio signal-to-noise levels were performed during laboratory tests. When one compares the D/U ratios where the subjectively rated tune-out points occurred in the iBiquity test report with the D/U ratios where the objectively measured 30 dB WQP S/N ratios occurred in the iBiquity test report, there is strong correlation. Thus, it appears that 30 dB WQP as measured on the test platform is the S/N ratio below which listeners will not listen to analog FM radio.

Using the subjectively-rated tune-out points listed in Table 19, and the 30 dB WQP S/N ratio objective criteria, the bounds within which tune-out occurs under each test condition can be determined from the FM IBOC test results. To determine these bounds, the two D/U ratios between which received analog FM audio quality in the presence of first adjacent channel FM IBOC signals went from above the tune-out point to at or below the tune-out point must be identified. Then, analog reception in the presence of first adjacent channel analog signals at these two D/U ratios must be compared with analog reception in the presence of FM IBOC signals at these D/U ratios. If there is no significant difference between the analog audio quality in the presence of first adjacent analog signals at both D/U ratios, and the analog audio quality in the presence of first adjacent FM IBOC signals at both D/U ratios, then it is reasonable to conclude that the introduction of FM IBOC would not have any significant impact under the given test conditions. However, if there is a significant difference between the analog audio quality in the presence of first adjacent analog signals at one or both of the D/U ratios, and the analog audio quality in the presence of first adjacent FM IBOC signals at one or both of the D/U ratios, then it is reasonable to conclude that the introduction of FM IBOC would have an impact under the given test conditions.

Employing this logic, testing was conducted that was designed to stress the system and find the points at which there was a potential for interference from the FM IBOC system. It was found that 20 out of 82 tests suggested a potential impact inside the protected contour.[23] Of the 20 tests that showed a potential for new interference inside the protected contour, 16 were laboratory tests. It is believed that the analog audio samples recorded in the laboratory were judged more critically by the listeners than were the samples recorded in the field because the automobile receivers were operating in stereo when the samples in the laboratory were recorded, and in mono when most of the samples in the field were recorded, and interference is more noticeable during stereophonic reception than it is during monophonic reception. Stereo reception occurred in the lab while mono reception occurred in the field because the receiver input signal level used in the laboratory was significantly higher than the receiver input signal level for many of the field tests, and at the lower receiver input signal levels the automobile receivers automatically switch to monophonic reception to reduce audible noise. Thus, one might expect the laboratory results to be more indicative of listener reaction when a pair of first adjacent stations are short-spaced and thus producing strong desired and undesired signal levels for listeners, a relatively infrequent occurrence. The

[23] Based on field test results, and laboratory results with 30,000K AWGN RF noise – see Section 4 above for additional information on use of 30,000K AWGN.

field tests, on the other hand, are believed to be more indicative of the typical first adjacent channel spacings that exist in the FM band.

Focusing on the field test data, only 4 of 18 tests would suggest the potential for new interference inside the protected contour. And, of these four tests, only one produced results with a confidence interval that indicates at least fifty percent of listeners would stop listening to the station due to the interference from the first adjacent IBOC station. These field test results are summarized in Table 20.

Table 20: Summary of 1st-adjacent FM IBOC impact inside protected contour

	FIELD TESTS	
RECEIVER TYPE	TOTAL	SHOWING NEW INTERFERENCE INSIDE PROTECTED CONTOUR THAT WOULD CAUSE AT LEAST HALF OF LISTENERS TO TUNE OUT
OEM auto	6	0
Aftermarket auto	6	0
Home hi-fi	3	1
Portable	3	0

Based on the results summarized in Table 20 it appears that the introduction of FM IBOC will have no significant impact inside the protected contours of FM radio stations.

4.12.2.2 1st-adjacent channel compatibility – outside the protected contour

The area beyond the protected contour requires a different type of analysis than the area within the protected contour because beyond the protected contour the question is not if there will be new interference, but rather how much. Stations are expected to receive interference beyond the protected contour even with the analog FM transmissions of today. To determine how much new interference might occur to analog reception with the introduction of FM IBOC, data was collected at a number of D/U ratios that occur beyond the protected contour.

Laboratory and field data was collected for 12 D/U ratios typically found outside the protected contour. The majority of this data was collected for the automobile receivers. There was a limited amount of data collected for the home hi-fi and portable receivers, and it served to confirm that these receivers are generally not capable of producing acceptable levels of audio quality when located beyond the desired station's protected contour due to analog first adjacent channel interference. Since there would in that case be no additional impact due to FM IBOC (from the listener's perspective), the data for these receivers is not included in this analysis.

All of the beyond-the-protected contour first adjacent channel data for the automobile receivers was analyzed and it was found that 21 out of 58 tests suggested that there would be some new interference outside the protected contour.[24] Of the 21 tests that showed some new interference outside the protected contour, 16 were laboratory tests. As discussed above, the receiver input signal level used in the lab for the +6 and -4 dB D/U ratio tests was considerably higher than the receiver input signal levels from many of the field test sites for these D/U ratios. When the field tests alone are considered, only 5 of 34 tests would suggest some new interference outside the protected contour. And, of these five

[24] As with the inside-the-protected contour data, only the results with 30,000K added were used from the laboratory. See footnote 23.

tests, only three produced results with a confidence interval that suggested at least fifty percent of listeners would stop listening to the station due to the interference from the first adjacent IBOC station. These results are summarized in Table 21.

Table 21: Summary of 1st-adjacent FM IBOC impact outside protected contour

	FIELD TESTS	
D/U RATIO (dB)	TOTAL	SHOWING NEW INTERFERENCE OUTSIDE PROTECTED CONTOUR THAT WOULD CAUSE AT LEAST HALF OF LISTENERS TO TUNE OUT
+4	2	0
-1	2	0
-4	6	1
-6	4	0
-8	2	0
-9	6	0
-10	2	0
-11	2	0
-12	2	2
-13	2	0
-14	4	0

It should be noted that, of the 34 first adjacent field tests for the automobile receivers, 24 (or 71%) were collected using rock or country programming as the desired audio. Six (or 17%) were collected with speech as the desired audio, and 4 (or 12%) were collected with classical music as the desired audio. Because the test results, in general, indicate that interference at a particular undesired signal level will be more annoying to listeners when the desired programming is speech than when it is rock or country music, it is reasonable to assume that FM IBOC will have a more significant impact on speech programming beyond the protected contour than the data in Table 21 suggest. Any impact from IBOC, however, for speech and other formats is expected to be limited by the fact that there are small geographic areas where listeners experience these levels of first adjacent interference and still receive adequate analog reception. Moreover, because any potential impact from IBOC will be limited to automobile receivers, the impact should be further reduced by the fact that the listener is mobile and will move through any areas of interference. As the D/U ratio changes dynamically with the movement of the automobile, any IBOC impact may quickly disappear.

It should also be noted that the perceived audio quality from the automobile receivers did not steadily decline as the interfering signal got stronger. There are several cases in the data where increasing the strength of the interfering signal actually improved the rating that the listeners gave to the desired audio. This is likely because automobile receivers are competitively designed for harsh reception conditions and, as interfering signals get stronger, circuitry inside these radios activates to perform functions such as switching to monophonic reception or narrowing the receiver's intermediate frequency bandwidth to better block out the interference. Laboratory testing by the NRSC subsequent to the release of the iBiquity FM IBOC test report has found that this sort of circuitry will activate in automobile receivers in the presence of strong interfering signals on second, fifth, tenth and twentieth adjacent channels. This is undoubtedly because this type of interference can occur anywhere within a station's listening area, and receiver manufacturers want their products to perform well throughout this area. This suggests that the introduction of FM IBOC may, in many cases, cause mobile analog reception outside the protected contour to become more monophonic than it is now. However, it is important to note that listeners today frequently receive a monophonic signal, even within the protected contour, and are satisfied with that analog reception. In many cases, listeners prefer unimpaired monophonic reception when compared to impaired stereo signals. Therefore, it can be assumed that the introduction of IBOC and any increase in monophonic reception will not degrade the listening experience in the majority of cases.

It appears that the introduction of FM IBOC will, in certain cases, have some negative impact on analog reception outside the protected contours of FM radio stations. This impact is most likely to be perceptible when the desired analog FM programming is primarily speech. Also, it is only expected to affect automobile receivers because home hi-fi and portable receivers are generally not capable of receiving good audio in the presence of first adjacent channel analog signals beyond the protected contour today. Moreover, because the level of severe first adjacent interference required for any IBOC impact is limited geographically to small areas, any potential impact will be further limited. It appears that the introduction of IBOC will not degrade the listening experience in the majority of cases.

4.12.2.3 NRSC Study on 1st-adjacent channel interference

To illustrate how one might go about predicting where potential areas of new interference might occur in an analog FM station's coverage area with the introduction of a first adjacent channel FM IBOC signal, the NRSC commissioned a study by the engineering consulting firm Denny & Associates, P.C., and TechWare, Inc., a software contractor with extensive experience predicting interference associated with the rollout of digital television. The study results are in Appendix I.

This study cannot be used to make general conclusions about the amount of interference that might occur with the introduction of FM IBOC because only six stations were studied. Furthermore, for the six stations that were studied it is not expected that all listeners in the areas where new interference is predicted would tune away from the desired analog station because of the interference. The subjective ratings of audio quality that were the basis for picking the D/U ratios at which new interference might occur are indicative of only half of all listeners finding the new interference so objectionable that they would tune away. Thus, the interference areas indicated in the study are really predicting areas where, at most, half of all listeners might be inclined to tune away. And, in some portions of these interference areas, the predicted impact would be on fewer than half of all listeners because the subjective evaluation results on which the predictions are based indicated that fewer than half of all listeners found that level of interference objectionable.

While the areas of interference predicted by the study may tend to overstate the potential impact of FM IBOC as just described, in some respects they may also understate it. The study assumes that the impact of FM IBOC on first adjacent analog stations will not be noticed at D/U ratios lower (*i.e.*, more negative) than -4 dB because it is assumed that analog reception at these locations is already impaired. Based on the field test data for speech programming, this appears to be an accurate assumption. However, speech programming samples were only collected at fixed locations in the field. Mobile field test results, which are arguably more illustrative of the performance of automobile radios, were only conducted for rock/country programming. These results indicate that both automobile radios produced audio that was acceptable to most listeners at the -12 dB D/U ratio when the undesired signal was analog, but unacceptable to most listeners when the undesired signal was FM IBOC. Thus, in the case of rock/country programming, the study results in Appendix I predict no interference in some areas where the test data suggests new interference may actually occur (*e.g.*, at the -12 dB D/U ratio). It should be noted, however, that while the +6 dB to -4 dB D/U criteria used to predict interference in the study causes the impact on rock/country programming at -12 dB to be missed, it also greatly exaggerates the impact on rock/country programming within the +6 dB to -4 dB D/U range because, within this range, the subjective test results indicate that listeners are less likely to find the impact of FM IBOC on rock/country programming to be objectionable than they are to find its impact on speech programming objectionable.

Overall, it is extremely difficult to produce a simple, set methodology that can easily be applied to all stations for predicting FM IBOC's impact on first adjacent channel analog reception. The impact that FM IBOC will have is very dependent on the type of receiver that is assumed, and on the programming being broadcast on the desired analog station. Furthermore, as discussed in Appendix I the strength of the two signals involved also plays an important role. It appears that when the two stations are closely spaced, and thus their signals are strong, automobile receivers are more likely to be operating in the stereo mode and listeners are therefore more likely to find first adjacent FM IBOC interference objectionable. However, when the two stations are farther apart and thus their signals are weaker, automobile receivers are more likely to be operating in the monophonic mode and listeners are therefore less likely to find first adjacent FM IBOC interference objectionable. To predict with any degree of confidence the amount of new interference that listeners of any particular FM station might experience as a result of the introduction of FM IBOC, all of these factors must be taken into account.

4.12.3 2nd-adjacent channel compatibility

The NRSC test program included tests to determine the impact of a 2nd-adjacent channel FM IBOC signal on an analog signal. As in previously discussed compatibility tests, the procedure here was to measure the S/N ratio in the main channel audio portion of an analog FM signal, first with an analog interferer, then with a hybrid FM IBOC interferer, and then to subjectively evaluate audio recordings made under these conditions.

The data from the (objective) S/N measurements for all four analog receivers are presented in Figure 20. In the top two graphs, data obtained on the automotive receivers is shown, indicating that these receivers were not impacted by the presence of the IBOC digital sidebands on the 2nd-adjacent channel interferer. This is most likely due to the fact that the automotive receivers have very selective front-end IF filters which eliminated the 2nd-adjacent channel interference.

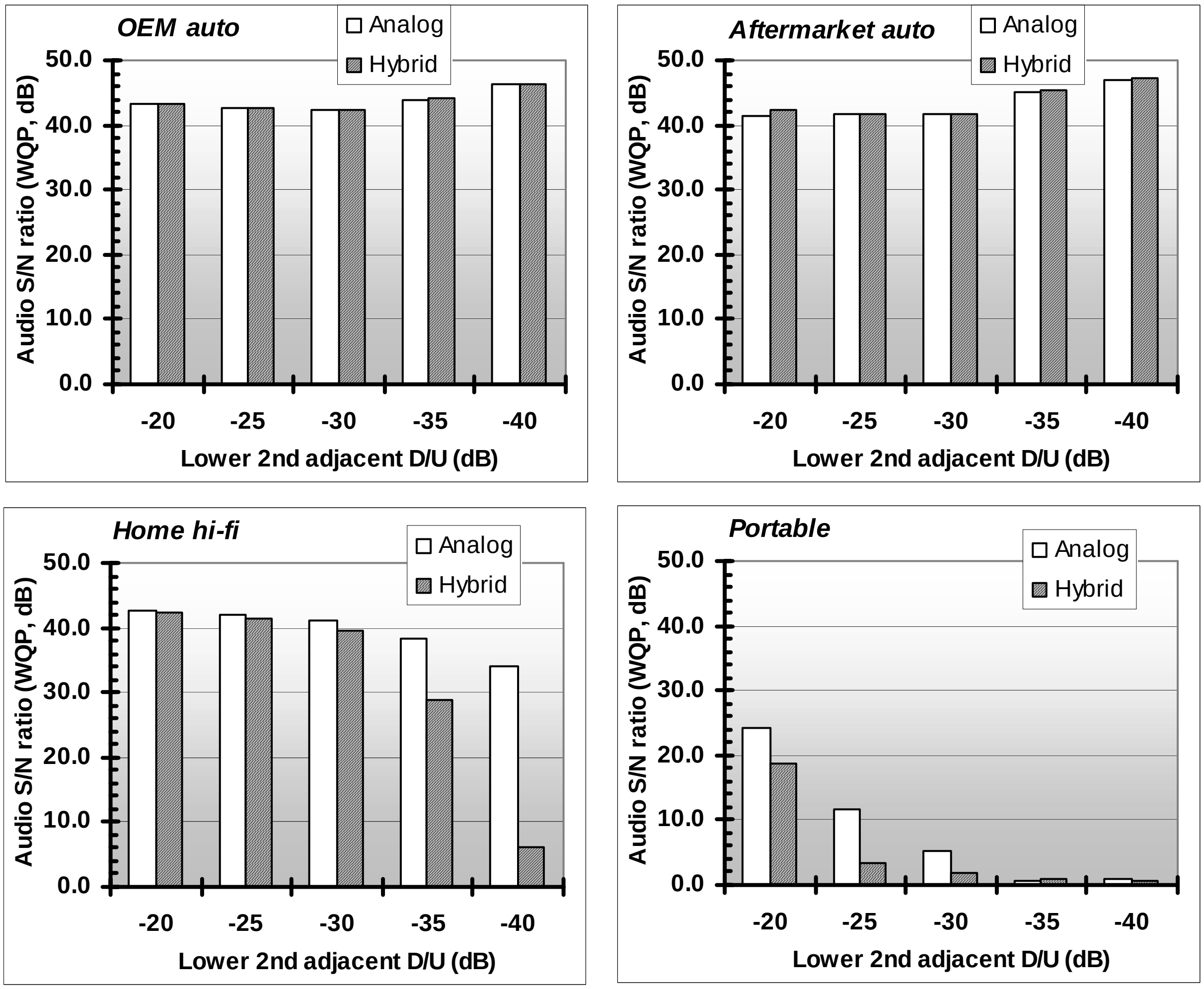

Figure 20. 2nd-adjacent compatibility – objective test results with analog and hybrid interferers (lower 2nd-adj., with 30,000K noise)

The graph in Figure 20 on the lower right shows that for the home hi-fi receiver, as the level of the 2nd-adjacent channel interferer was increased, there was some impact on the desired analog audio signal due to FM IBOC. In particular, at D/U ratios of -35 dB and -40 dB, the S/N ratio in the desired main channel audio was reduced by 10 dB and 28 dB, respectively, with respect to the S/N ratio achieved when an analog (i.e. non-hybrid IBOC) interferer was present. The subjective results for this receiver are shown in Figure 21, where in the -40 dB case the audio quality in the desired analog signal is reduced from "fair" to "bad."

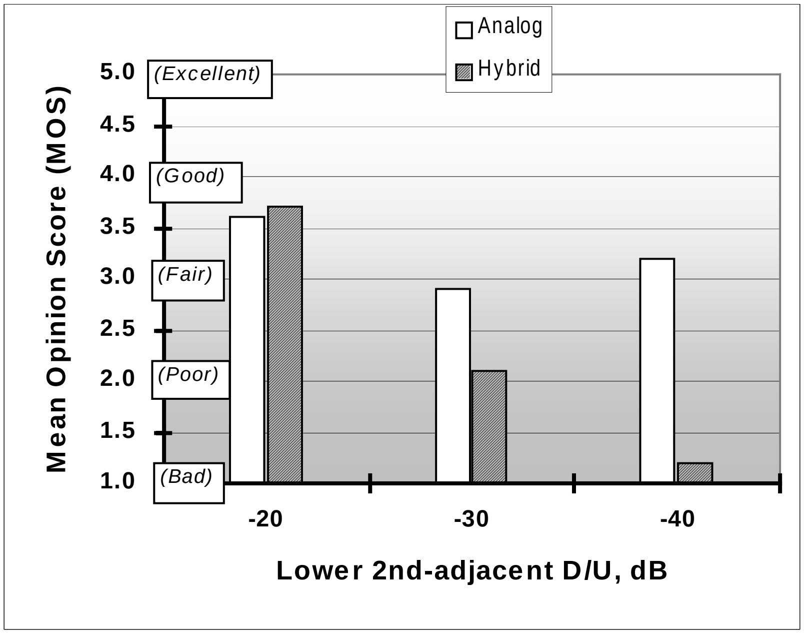

Figure 21. 2nd-adjacent compatibility – subjective test results with analog and hybrid interferers (home hi-fi receiver, lower 2nd-adj., with 30,000K noise)

There are a number of reasons why the hi-fi receiver results presented here are of less concern than the 1st-adjacent channel interference results (outside the protected contour) presented in Section 4.12.2.2 above. Because this receiver is stationary, its antenna can be oriented so as to minimize adjacent channel interference problems. In addition, testing done on other hi-fi receivers (see Appendix H) suggests that the hi-fi receiver tested used in the NRSC FM IBOC tests is among the most susceptible to 2nd-adjacent channel interference and that other hi-fi receivers will be affected less.

In the final graph of Figure 20 (in the lower right) for the portable receiver, again some impact due to the presence of the IBOC digital sidebands on the hybrid interferer is noted, however in this case the S/N ratio in the desired main channel audio signal is so low (irrespective of whether the interferer is hybrid FM IBOC or not), the small additional interference due to the FM IBOC digital sidebands is not significant.

4.12.4 Findings

For the three cases considered, the following findings apply regarding the introduction of hybrid FM IBOC into the FM band:

Co-channel interference: no impact on analog reception (by design).

1st-adjacent channel interference: listeners within the protected contour should not perceive an impact, but a limited number of listeners may perceive an impact outside of the protected contour under certain conditions.

2nd-adjacent channel interference: NRSC tests indicated that some receivers (with performance similar to the NRSC analog automotive and portable receivers) should not experience an impact on performance due to 2nd-adjacent channel hybrid FM IBOC interference, however, a very limited number of receivers (with performance similar to the home hi-fi receiver used in the NRSC tests) might experience a negative impact for -30 to -40 dB (and more negative) D/U ratios.

4.13 Impact on SCA reception

Subcarriers are utilized on slightly less than half of FM stations, according to a 1997 report by NAB.[25] Of particular interest are subcarriers utilized for radio reading services and other audio services operating with analog subcarriers, the RBDS subcarriers delivering station information to consumer receivers so equipped, and data subcarriers, including RBDS and DARC technologies, providing proprietary data services through third parties on a subscription basis.

The NRSC test plan included testing of subcarrier receivers for compatibility with FM IBOC signals on the host and first and second adjacent stations. iBiquity submitted the results of this testing, which included a report on objective test data from the ATTC and a summary of Dynastat subjective testing on lab and field test recordings. The Evaluation Working Group prepared its own detailed evaluation of the results, which is presented in Appendix J.

4.13.1 Findings

In order to evaluate any impact of IBOC on SCA services, the NRSC developed test procedures and witnessed SCA compatibility tests for the IBOC system. Laboratory tests were performed at ATTC and field tests were performed using the facilities of WPOC and experimental station WD2XAB.

The NRSC recognizes that adequate reception of SCA audio is a complex procedure that is very dependent on a host station's operating parameters, distance from transmitter, and adjacent channel signals. In most cases, analog reception of SCA programming is optimized by listeners orienting receiving antennas for best-recovered audio. The limitations of SCA reception are well known to users of analog SCA services and are for the most part accepted and tolerated. It is expected that a new generation of digital technology will be offered by IBOC, with its auxiliary capacity, that will provide significantly improved reception and that existing analog SCA services will over time migrate to them.

During the course of evaluating the various laboratory analog SCA test results, both with and without the addition of IBOC, the NRSC discovered what appear to be significant performance disparities among the receivers used for the tests. In some tests, little or no impact was observed after the introduction of an IBOC signal. However in other tests significant impact was noticed. Similarly in field tests with and without IBOC, some receivers performed well, while others failed totally.

At the time the SCA tests were developed by the NRSC, the DAB Subcommittee felt that the SCA test program would be sufficient to determine conclusively whether or not the adoption of IBOC by FM broadcasters would have an adverse impact on SCA reception. Indeed, careful evaluation of test data shows that the digital SCA services tested (RDS and DARC) should not be adversely impacted by IBOC.

For the case of analog SCA services, some questions still remain as to the impact of IBOC on such services. In order to answer these questions and to provide additional clarity to this matter, iBiquity, National Public Radio and the International Association of Audio Information Services have agreed to expeditiously perform a series of additional tests for the purpose of determining how certain SCA receivers will perform after IBOC is implemented on host and adjacent channel stations. The NRSC

[25] See "NAB FM Subcarrier Market Report/Technology Guide," NAB, 1997, pg. 48.

encourages the rapid completion of these tests in time to provide meaningful input to the FCC for its consideration.

4.14 Industry subjective evaluation

In order to ensure that radio broadcasters have a part in the direct subjective evaluation of IBOC test data, the NRSC worked with iBiquity to develop and conduct an Industry Evaluation. The evaluation was conducted September 5-7, 2001 at the NAB Radio Show in New Orleans.

A total of 61 volunteers from the radio broadcast industry participated in the program. Participants were chosen from a list of volunteers recruited by the NAB through direct solicitations distributed via the Web, email and print.

The methodology used in this evaluation followed very closely that used at Dynastat as described earlier in this report. However, Dynastat chose as its participants members of the general public who were not necessarily associated with the radio industry. Audio samples used were obtained from digital recordings representing a variety of relevant laboratory and field tests of the IBOC system.

The results of the Industry Evaluation, for all practical purposes, were the same as those obtained in the Dynastat program, demonstrating that the broadcast industry participants were no more or less affected by the various test audio samples than the participants from the general public.

Data from the Industry Evaluation is attached to this report as Appendix K.

NRSC Document Improvement Proposal

If in the review or use of this document a potential change appears needed for safety, health or technical reasons, please fill in the appropriate information below and email, mail or fax to:

National Radio Systems Committee
c/o Consumer Electronics Association
Technology & Standards Department
1919 S. Eads St.
Arlington, VA 22202
FAX: 703-907-4190
Email: standards@ce.org

DOCUMENT NO.	DOCUMENT TITLE:	
SUBMITTER'S NAME: COMPANY:		TEL: FAX: EMAIL:
ADDRESS:		
URGENCY OF CHANGE: _____ Immediate		_____ At next revision
PROBLEM AREA (ATTACH ADDITIONAL SHEETS IF NECESSARY): a. Clause Number and/or Drawing: b. Recommended Changes: c. Reason/Rationale for Recommendation:		
ADDITIONAL REMARKS:		
SIGNATURE:		DATE:

FOR NRSC USE ONLY

Date forwarded to NAB S&T: ______________________

Responsible Committee: ______________________

Co-chairmen: ______________________

Date forwarded to co-chairmen: ______________________

CEA

Consumer Electronics Association

NAB

NATIONAL ASSOCIATION OF BROADCASTERS