Wheatstone WHITE PAPER

The Curious Behavior of Consumer FM Receivers During Hyper-modulation

By Jeffrey A. Keith, CPBE, NCE
Senior Product Development Engineer

Wheatstone Corporation

Abstract

FM audio processor technology has significantly advanced since the early days. Now, sophisticated multiband gain controllers and absurdly complex peak limiting schemes create on-air audio loudness never before achievable, and with good subjective quality. Most FM processor developers' goal has been to improve their algorithms so that FM can sound better at the previous technology's loudness levels, but that has often meant that stations push new processing technologies harder to achieve more loudness at the previous distortion levels. Many FM's today operate with 120% or higher modulation while also aggressively processing their audio at the same time. While such a tactic makes an FM station very loud, what has not been recognized is the negative

Background

As an audio processing designer I've had the privilege of visiting a lot of radio stations over the years to install and tune broadcast transmission equipment. One of the things consistently noted was that the higher a particular station's modulation was the more radios there were that showed noticeably distorted audio. This was especially true when the station was also being very heavily processed. This created a question that needed an answer: if certain radios couldn't be relied upon to judge a station's audio quality, then what does the average listener's inexpensive radio sound like when tuned to a "hyper-modulated" FM station?

When 100% Modulation Became 110%

In April of 1984 the Federal Communications Commission (FCC) relaxed the FM modulation rules to help stations recover some of the main channel modulation being lost when transmitting subcarriers. The newly proposed 110% modulation limit seemed reasonable; 82.5 kHz deviation rather than 75 kHz was deemed safe for virtually all FM receivers of the day [1]. The increase in occupied bandwidth was thought by experts to be small enough to not create interference issues for adjacent channel stations.

During the ruling's comment period [2] the Consumer Electronics Group of the Electronic Industries Association (CEG/EIA) cautioned the FCC that "modulation above 110% had a good chance of compromising the performance of consumer receivers and deteriorating the perceived quality of FM service". Even though the CEG/EIA's opinion likely had merit, many FM stations today utilize modulation much higher than 110%.

FM Receivers' Poorly Documented Limits

As broadcast engineers we know a lot about our end of the FM broadcast signal chain. On the other hand, we probably don't know a lot about the radios that our listeners use to hear our signal. As FM receiver technology has evolved over the years radio IC manufacturers have put more and more 'clever' circuitry into those ICs in an attempt to solve issues due to weak signals, multipath, impulse noise and interference. Reviewing the data sheets for several of the more recent receiver ICs revealed that there are all kinds of specialized and hidden functions inside those ICs, and many of them are 'radio manufacturer' customizable via software.

While most AM/FM/HD radio ICs have hidden and programmable features to manage behavior in the presence of noise, multipath, and interference, a few of the newer chips [3] go even further to detect 'high deviation' (we would call it over-modulation) and engage variable bandwidth filters or impulse noise circuits to 'fix' what the IC thinks is bad audio. According to a warning in one of the IC data sheets, "when this feature is active it can disrupt the audio in unpleasant ways". Could this be an explanation for times in the field where certain radios were observed to be distorted when the station's modulation was well above 110% but those same radios sounded a whole lot better if the modulation (not the processing) was lowered?

Of course, a station's listeners don't even know their radios have these hidden capabilities so they won't understand why their radio does strange things only when it's tuned to certain FM stations. They will think it's the station, not the radio, right? To better understand why a listener's FM radio might not 'like' a hyper-modulated signal, we first need to look at some of the tradeoffs and variables associated with the design and manufacturing of consumer-grade FM receivers.

Here are four:

- Consumer receivers are manufactured at the lowest possible cost. When a company manufactures millions of radios and can save a dollar of build cost on each one, how much money has been saved? A low build cost also implies little attention to optimizing radio-to-radio consistency and few would even notice, too; how often are two of the same model radios directly compared to each other?

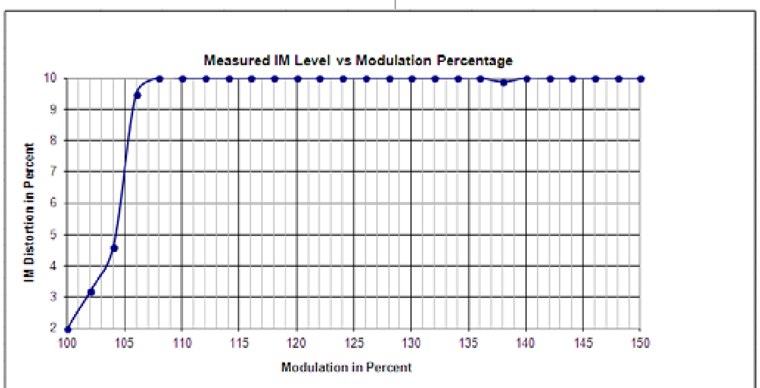


FIG 1
Eton Traveler Iii, Model NGWTIIIB -IM Distortion

- In order to build FM receivers that behave in benign ways in today's crowded RF spectrum, designers often give them restrictive intermediate frequency (IF) bandwidths. The IF bandwidth of one radio measured [4] was barely 100 kHz wide (+/- 50 kHz) at the 3dB points. This radio was perceptibly distorted when tuned to a normally modulated FM station. Below is the distortion plot for that receiver, the worst of those measured.

- Another factor rarely considered by both FM broadcasters and radio designers: is there any extra headroom in the receiver's FM detector, stereo demodulator (if equipped) and pre-volume control audio circuitry? Recent correspondence with Silicon Laboratories [5] revealed that designers of modern receiver chips don't design their IC's to accept FM modulation levels much above 100% and the reason is clear; those designers will generally find just two specifications within the world's voluminous broadcast regulations: 82.5 kHz deviation (110%) within the United States, and 75 kHz (100%) elsewhere. With this data in hand the radio's design team knows two things: (1) there is no need to design a radio to accommodate higher modulation, and (2) if it will cost more to do it, they won't.

- A final revelation has to do with the extreme programmability of modern receiver ICs. Even though two different manufacturers might use exactly the same receiver chip in their products, one manufacturer might program that chip to behave completely differently than the other. What this means is that strictly judging radios by the receiver chip they use doesn't really tell the whole story. There are a lot of variables 'under the hood' of newer receiver ICs that, as users, we not only can't see, we also can't change. Nor do we have a way to see how the chips have been programmed to operate by the radio's manufacturer.

During research for this paper, I posed a question via email to several of the FM receiver chip manufacturers: "if consumer FM receivers targeted for the global FM broadcast market are designed for 75 kHz deviation and 100 kHz channel spacing (they are, it's the most common) how do their receiver chips behave when tuned to U.S. FM stations using 82.5 kHz (110%) or higher deviation?"

In response I received the latest AM/FM/HD receiver chip data sheets. Those data sheets were a treasure trove of information, however, that helped confirm an ongoing suspicion about AM/FM receiver chips in general and their inability to cleanly handle more than 75 kHz deviation [6].

Another 'data sheet discovery' was that many of the digital AM/FM/HD chip manufacturers specify harmonic distortion at only 22.5 kHz deviation (33%) modulation [7][8]-[9] and do not specify intermodulation distortion.

Not every consumer FM radio will have audio quality issues when tuned to a hyper-modulated station, but formal testing of a select group of "consumer" FM receivers revealed that many do. An important data point from the tests is that the more recent the radio, the more intolerant of high modulation it seemed to be. The implication is that unless receiver chip manufacturers go back to doing things the old way (doubtful) future radios could be even more intolerant of hyper-modulation than those of today.

Selecting FM Receivers To Test

To learn how consumer radios behave when tuned to a hyper-modulated station, a representative sample of the type of radios used by the general public must be tested. The number of radios to test isn't a technical problem, but a practical one; a thousand is too many and one is too few. For the purposes of this research fifteen radios were selected; five each from three categories; "portable", "tabletop", and "automobile".

The task of selecting the radios was assigned to a fellow broadcast engineer and avid radio collector [10] using three criteria: (1) each radio must have been sold to the general public as a new product within the United States in the last 25 years, (2) all must be as typical as possible to those likely to be purchased by casual FM listeners within the general public, and (3), they may not have cost more than $50 US dollars when they were new.

By excluding audiophile or other 'high end' receivers it was possible to concentrate solely on the type of radios used by listeners in the general public. How many people spend hundreds of dollars on an FM radio just to listen to their favorite station? How many spend $50, or even $25?

Quantifying Modulators

Like the average consumer receiver, FM broadcast exciters only have to be designed to linearly achieve 110% modulation. That is after all the only modulation headroom specification that they must meet. Can modern day exciters achieve more? Probably. Can they achieve a lot more? We don't often know. How far above 110% they can cleanly modulate is usually not among the published specifications.

The station's FM exciter plays an extremely important role in the overall FM broadcast transmission system, but trying to include fair brand and model representations from myriad exciter manufacturers would unreasonably complicate the research phase of this paper by orders of magnitude. To eliminate the 'brand bias' issue, a specialized low power, wide deviation capability FM exciter was designed and built. With its modulation capability of 250 kHz (333% modulation) and THD and IM distortion below 0.05%, it adds no uncertainty to the measurements.

Getting Useful Data

The best way to measure the behavior of a radio tuned to a hyper-modulated FM signal is to get access to its demodulated and de-emphasized FM audio, preferably prior to any power amplifiers. Unfortunately, such access can be difficult on most radios without at least some disassembly. For consistency, a radio's headphone output or its speaker leads were used to gain access to output audio (getting data from automobile radios was especially challenging).

During an earlier research project on FM receiver behavior [11] an amplitude-swept 400Hz tone was used to plot different radios' audio input/output transfer function at various modulation levels. A different approach was taken this time to achieve three primary goals: (1) better quantify a listener's perception of what could be perceived as objectionable distortion as modulation is increased, (2) use a measurement technique that could be replicated by others wishing to do their own tests, and (3), show the data in a way that helps readers understand that the results of the measurements ARE important.

Not All Distortion Is Bad

Psychoacoustics, the study of human hearing, has been a fascinating research subject for many decades. One of the things learned about our 'hearing' is that every one of us hears things differently. Like our other senses; touch, taste, sight and smell –– hearing is a very personal experience. Our perception of distortion is very personal too – what one listener hears – and loves – another listener might find extremely objectionable.

Many different kinds of audio distortion have been identified, but the one that we find most objectionable is intermodulation distortion (IM). In fact, IM distortion is often more objectionable than harmonic distortion even when the harmonic distortion is many times higher. This oddity is especially true when the components making up the harmonic distortion are mostly even order [12]-[13]-[14].

There have even been audio 'enhancement' products designed and marketed over the years that purposely generate even order distortion – some even patented [15][16]. Why do we prefer harmonic distortion over intermodulation distortion? One theory is that due to the ear's natural nonlinearities (which generate a form of IM distortion) the internal and external IM distortions somehow interact to make the external IM distorted signal sound worse [17].

Our lower tolerance for IM distortion makes it an appropriate metric for determining what sounds 'objectionable' to an average FM listener. But, no radio is perfectly linear, so every radio will have some level of residual IMD. To discount this, an IM distortion plateau of 2% was selected, below which distortion was not tabulated. Audio purists will find 2% IMD extreme and while they would be correct in that context, the data sheets revealed that most FM receiver IC's have harmonic distortion well above a 'purist' threshold. Plus, only in very rare cases is IM distortion lower than harmonic distortion, so the unpublished IMD spec hints that IMD is higher than the published harmonic distortion.

A static level of 10% IMD is very audible to almost everyone. It is also the upper limit of my audio analyzer and is the reason why the distortion plots 'peg out' at 10%.

The purpose of the receiver tests was not to look for a fixed distortion number. In fact we really don't care what a particular radio's distortion is at 110% modulation. Nor do we broadcasters have any control over it. But we should be very interested in the distortion trend of the radios being used by our listeners when we are modulating above 110%.

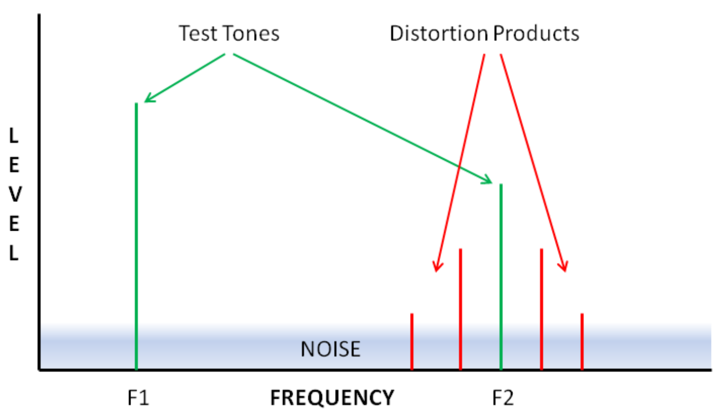
Measurement Methodology

The FM exciter/modulator used for the distortion tests was previously mentioned. A Hewlett-Packard 8901A Modulation Analyzer was employed to accurately measure modulation at and above 100%.

The SMPTE standard IMD test was chosen as a test signal with two tones; 60Hz and 7 kHz at a 4:1 ratio. After 75uS FM pre-emphasis the 7 kHz tone will be within 1.25dB of the 60Hz tone, better representing the 'flatter' spectral balance of pre-emphasized and processed audio. Receiver de-emphasis will bring the tones back down to their original 4:1 ratio prior to measurements.

A Neutrik A2D Audio Test System was used as the audio signal generator and analyzer. Its signal generator was configured to perform an amplitude sweep using the SMPTE standard IM test signal. The amplitude sweep was set to ramp the modulation level over a +6dB range to create a modulation swing between 100% and 150%.

The audio analyzer was used to measure and plot SMPTE IM distortion of the receiver's audio output as modulation was raised. The analyzer's input signal was the left channel output of the receiver being tested.



$$IMD = \frac{Sidebands}{Signal\ (f2) + Sidebands}$$

FIG 2
SMPTE Intermodulation Distortion Spectrum

The image in Figure 2 shows the audio spectrum when an SMPTE IM test signal is present and the device under test is generating IM distortion. The 60Hz and 7 kHz tones are labeled "Test Tones' and shown in green. The distortion products generated by the device are labeled "Distortion Products" and shown in red. A perfect receiver would have no distortion products – only the (green) 60Hz and 7 kHz tones would be present.

As a receiver becomes nonlinear as modulation is increased, it will distort the test signal and create sidebands spaced at 60Hz intervals either side of the 7 kHz tone. The higher the level of these sidebands, the more distorted the receiver's audio.

Test Bench Confirms Field

It was found that about half of the receivers tested added significant IM distortion at modulation levels as low as 120%. This was also in agreement with times in the field where a program director's car radio sounded fine but the one in the general manager's office was distorted – regardless of what brand of processor was on the air.

Anecdotes are one thing, but they do not replace data. The following graphs show how the average consumer radio's perceived audio quality changes as modulation is raised above 100%. The graphs are shown in the order of the three radio categories; portable, table top, and automobile. Data from five radios within each category was averaged to arrive at the 'average' plots for each radio category.

Figure 3 shows the average IM distortion over all of the receivers tested as modulation was raised from 100% to 150%.

The IM distortion percentage is far less meaningful than the slope of the distortion increase as modulation is raised. In some radios, especially newer ones, the distortion trend was very dramatic once modulation exceeded 110%. In all of the radios tested distortion rose quickly once the modulation exceeded 120-125%.

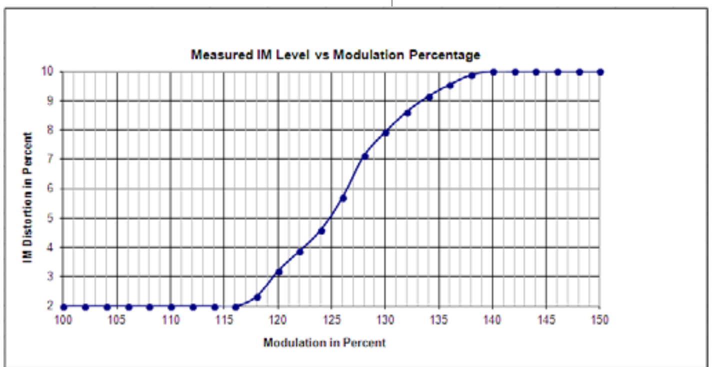


FIG 3
Average IMD Increase Vs. Modulation

The plot in Figure 3 is the most important of all because it shows the average distortion of all of the radios as a group. An individual radio's behavior may be curious in isolation, but it does not show what the station's listening audience might hear as a group. Therefore, and other than Figure 1, individual radio's distortion plots are not included here. Individual radios could be much better or much worse than the average, but a radio station has no means to isolate listeners with just the bad radios to make sure they get a better one.

The following plots show the average distortion behavior for the individual groups of radios; portable, table top, and automobile as modulation increases to 150%.

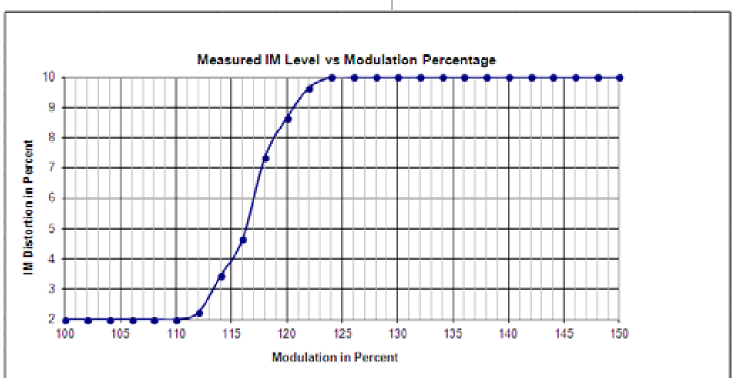


FIG 4
Average IMD Behavior – Portable Radios

Portable radios (Figure 4) appeared to show a consistent intolerance for higher modulation levels. This concurs with observations in the field where portable receivers seemed to sound more distorted than other radio types when tuned to a loud FM station.

The reason for this difference is not clear. Perhaps because portable radios have lower operating voltages their designers traded signal to noise performance for headroom, making such radios have issues earlier than radios operating

on higher voltages? Remember also that the volume control is after the circuitry being referring to when 'lack of headroom' is mentioned. When a listener adjusts his radio's volume control it does nothing to reduce the distortion that may be occurring before the volume control.

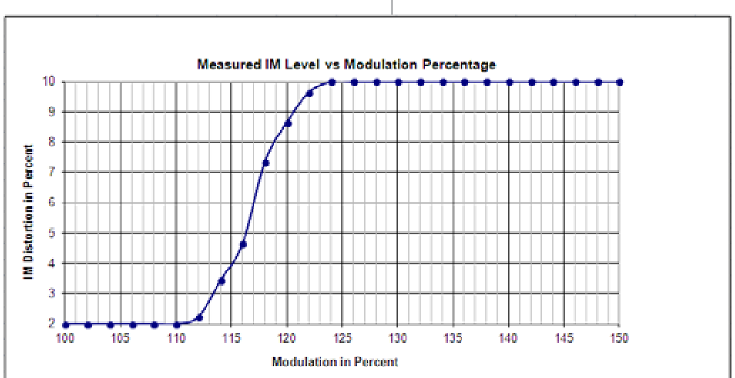


FIG 5
Average IMD Behavior – Tabletop Radios

Figure 5 shows the average table radio which fared better than the portables. Again this may be due to factors relating to available power supply voltages. Possibly supporting this hypothesis is that one of the portable radios tested utilized the same manufacturer's FM/AM receiver chipset as a tested table top radio, and the portable's distortion was much worse.

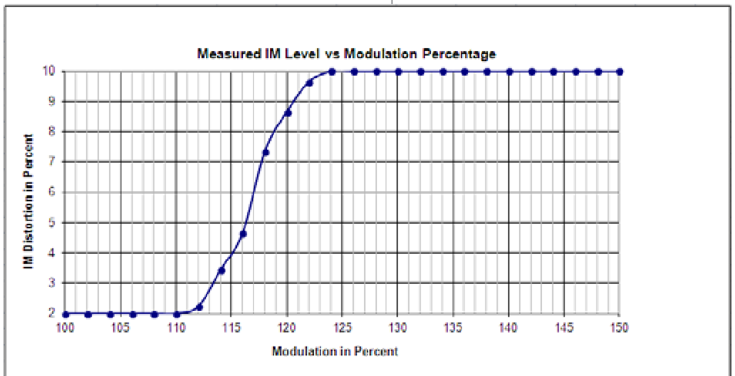


FIG 6
Average IMD Behavior – Automobile Radios

Figure 6 shows that of all the radios tested, automobile radios were the most linear, with several accepting modulation beyond 120% without generating the high IM distortion of other radios. However, none of the automobile radios was able to maintain acceptable (<5%) IM distortion when modulation was above 133%.

Conclusions

It seems plausible that 115-120% modulation is all that the average consumer FM receiver can accept without generating obnoxious distortion. This modulation percentage is based on the average across all three radio types. If a significant portion of the audience is using portable or table top radios, and if perceived audio quality is an important consideration for the station, then modulation levels below 120% may be a necessity.

Another factor to consider is that at high modulation levels, audio processing density comes into play. As the program material is processed harder and its peak to average ratio reduced, modulation spends more time up at the extremes which then has a radical effect on perceived distortion. Under these conditions audio quality can appear worse than if the station was using high modulation but lighter processing.

As conscientious broadcast engineers we work very hard at keeping our studio and transmission facilities top notch. But our ‘transmission systems’ don’t stop where our signal leaves the antenna and so our listener’s radios can play an unknown role in ratings, long term listening habits, how our signal sounds to the masses, and how successful our station is. It seems important to realize that even though we have absolutely no control over our listeners’ radios, those radios are still an important part of our overall transmission system. In fact they are the termination point for our station’s transmission system!

This research brought to light some important revelations about consumer receiver behavior whenever an FM station is modulating above 110%. It appears that even if it’s playing its listeners’ favorite songs, a station using hyper-modulation might be seeing its listenership trending down without anyone at the station realizing why.

Closing Thoughts

- Increased modulation brings with it increased RF bandwidth. If the station is operating on a multi-station combined system, finite filter bandwidth within the combiner system could create issues that might be absent at lower modulation levels. FM antenna bandwidth is rarely an issue on a properly designed system.
- During the design of today’s FM HD radio technology, bandwidth requirements were predicated on 110% modulation of the analog channel. An analog FM modulation level of 130% creates a minimum RF bandwidth of 225 kHz (+/112 kHz) [20]. Because FM sidebands don’t abruptly stop, but extend infinitely on either side of the carrier, excessive modulation can cause the station’s analog signal to encroach the spectrum occupied by its primary HD carriers which reside at +/- 164 kHz [21].

- During high modulation, multipath effects (not multipath itself) can seem worse on some receivers than when modulation is lower. This is a receiver-induced effect, not a transmitted one, and therefore is very highly receiver and receiver location dependent.
- Receiver distortion, when combined with high modulation and the transmission of low bitrate audio, can cause a station to sound far worse than when either linear audio is being aired or when modulation is lower. Aggressive audio processing exacerbates this effect.
- Audio processing and its relation to transmitted audio density were previously alluded to. In any broadcast system, the more time the program audio spends at the upper extremes of modulation, the more noticeable all system-related nonlinearities and their distortions become. Because clipping causes the signal to spend more time in the nonlinear behavior regions of the system, heavily clipped audio could be problematic, especially for portable receivers.

References

[1] 47 CFR-2012-title 47-vol 4-sec 73-1570(b)(2).

[2] BC Docket 82.536 (2)(a)(b), (3), pp 2.

[3] ST Microelectronics TDA 7504 AM/FM receiver data sheet, Fig 4 and pp 24-25.

[4] Eton Traveler III, Model NGWTIIIB.

[5] Personal email correspondence, Silicon Laboratories, Case Numbers 00056656/00056814, product reference Si4688-A10, Si4730.

[6] NXP Semiconductors – TEA6848L, In Car Entertainment Tuner data sheet, pp 10, section 7.6, "IF2 Filter Gain Alignment".

[7] NXP Semiconductors - TEF6902A FM tuner IC data sheet, pp 2-3.

[8] ON Semiconductor - LV24250 FM tuner IC data sheet, pp 2.

[9] ST Microelectronics - TDA7706 Highly Integrated tuner for AM/FM/HD data sheet (companion IC to ST Microelectronics STA680 HD Radio Decoder).

[10] Erickson, M.K., Audio Processing Systems and Support Engineer, Wheatstone Corporation.

[11] Keith, J.A., Processing for Today's Audio, Central Canada Broadcast Engineers conference, September 2009.

[12] "Types of Audio Distortion", http://parallelhomeaudio.net/TypesAudioDistortion.html.

[13] "Intermodulation Distortion",

http://en.wikipedia.org/wiki/Intermodulation

[14] "Understanding Audio Distortion", http://www.rtype.org/articles/art-130.htm.

[15] Knoppel, Curt A., US Patent Number 4150253, "Signal distortion circuit and method of use".

[16] Exciter effect, Aphex Aural Exciter,

http://en.wikipedia.org/wiki/Exciter_%28effect%29

[17] Jahn, A. F., Santos-Sacchi, J., "Physiology of the Ear", 2nd edition.

[18] "Tests of Audio Amplifiers in Accordance with Standard IEC 60268-3", Rhode & Schwarz application note, Chen, Jenny, May 2007.

[19] Audio Precision Knowledge Base, "More About IMD", February 01, 2013.

[20] Carson, J.R, "Notes on the Theory of Modulation," Proc. IRE, vol. 10, pp. 57-64, February 1922.

[21] Maxson, D.P., "The IBOC Handbook", "Understanding HD RadioTM Technology", 2007