VORSIS Application Note

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Ten-Band Spectral Limiter with Adaptive Filter Bank and High Performance AM Audio Processing

October 2008 - Jeff Keith

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Background

Competent audio processing for the AM band is special – it must be specifically tailored to a very challenging transmission medium and meet two important and opposing technical goals; generating maximum coverage area for the radio station *and* delivering the best possible audio quality at the listener's receiver.

Up to now, audio processors targeted to the AM broadcast market appear to have relinquished potential technical capability in order to either reduce design complexity or increase ease of operator setup. While such processors can no doubt 'put a signal on the dial' they can't deliver maximum performance where it counts the most – out in the far field at a listener's receiver.

This is the story of the Vorsis AM-10HD, a highly specialized audio processor built specifically for the unique challenges of AM. It was born when we combined our Digital Signal Processing (DSP) expertise with ingenuity, extensive knowledge of AM technologies and the limitations of today's consumer receivers, and an obsession to build the most powerful AM audio processor ever conceived.

A Short AM Tutorial

The invention of amplitude-modulation (AM) paved the way for more than one station to send signals to distant receivers. Before this, spark-gap radio was *it* and operating just one transmitter blanketed the entire radio spectrum with noise. It was great if you were 'into' making big sparks, but definitely not very useful otherwise.

Credit for the invention of AM belongs to Reginald Fessenden and Lee de Forest (inventor of the Audion, the first amplifying vacuum tube). On the evening of December 24, 1906 Fessenden used a 2kW Alexanderson alternator operating at 100 kHz to make the first radio *audio* broadcast from Massachusetts. Ships at sea heard a broadcast of him playing 'O Holy Night' on the violin (it *was* Christmas Eve!). This was the first documented instance of sending information in the form of 'audio' via amplitude modulated radio waves to distant receivers.

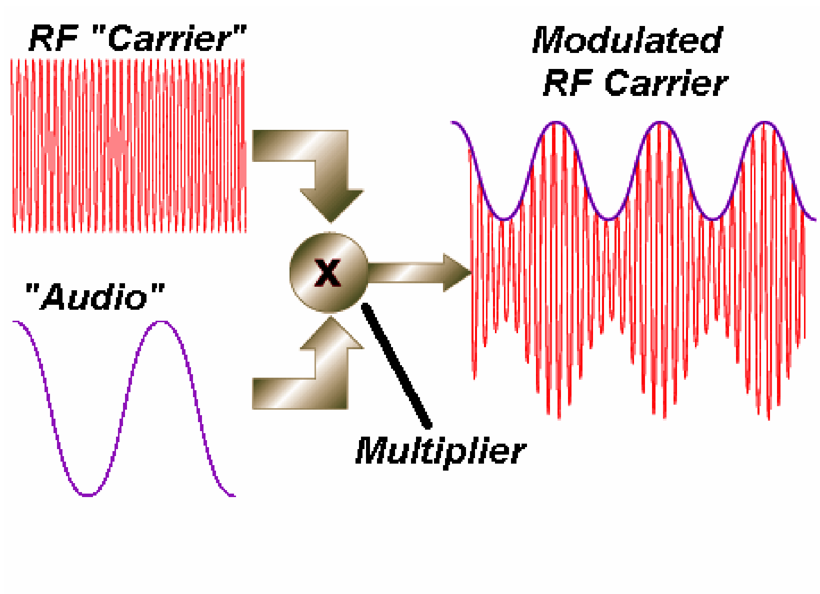
In order to create an Amplitude Modulated radio signal the amplitude of a radio frequency (RF) carrier is made to vary (modulate) in accordance with a desired audio signal. The result is a varying RF 'envelope' – it is this RF envelope that carries audio information to a distant receiver. The RF carrier has no purpose in carrying information – only the pair of sidebands above and below the carrier frequency generated by the modulation process actually carries information.

In conventional AM the two sidebands are redundant – both carry the same information. Such redundancy certainly wastes power because an AM receiver needs just *one* of the sidebands in order to extract the original audio, and conventional AM puts the same power and information into *both* sidebands.

There are other forms of Amplitude Modulation such as Single Side Band (SSB) and Double Sideband Suppressed Carrier (DSSC) where the sidebands or the carrier are manipulated to reduce or eliminate one or the other. We won't be talking about those here…

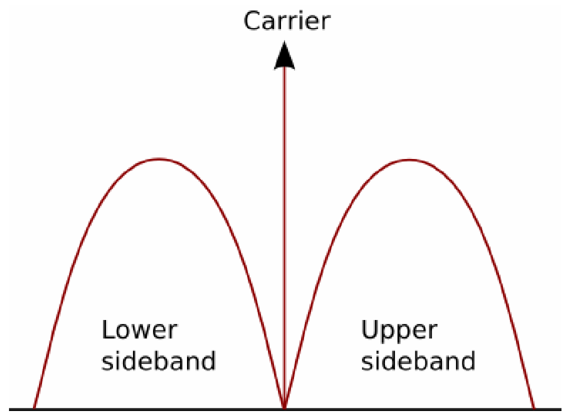
Creating the AM Signal

In order to generate an AM signal one needs only an "RF carrier" and an "Audio" source and a means to make the carrier wave *wiggle* along with the Audio signal. The most common way to do this is to simply *multiply* the RF carrier by the audio signal as shown in the diagram below.

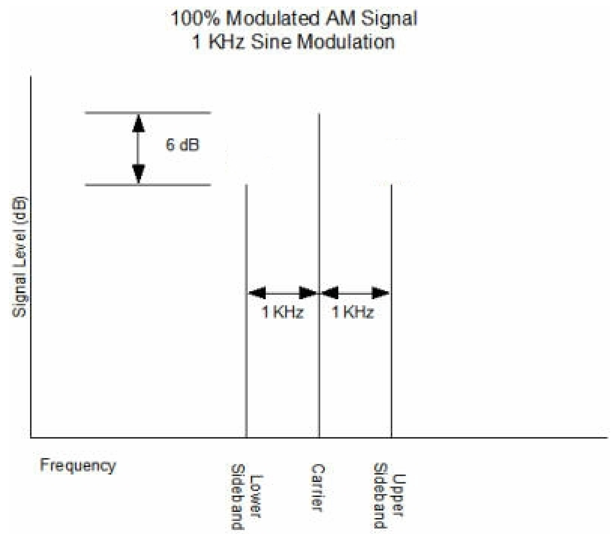


The output of this scheme is the modulated RF envelope we spoke of earlier which can then be demodulated by an AM receiver tuned to the RF carrier's frequency.

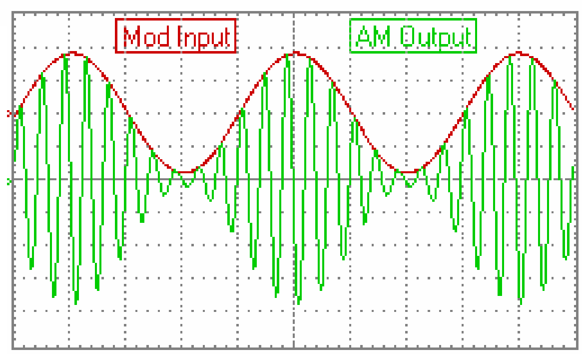
In the frequency domain the audio signals appear as sidebands above and below the frequency of the RF carrier and spaced away from the carrier by value of the highest modulating frequency.



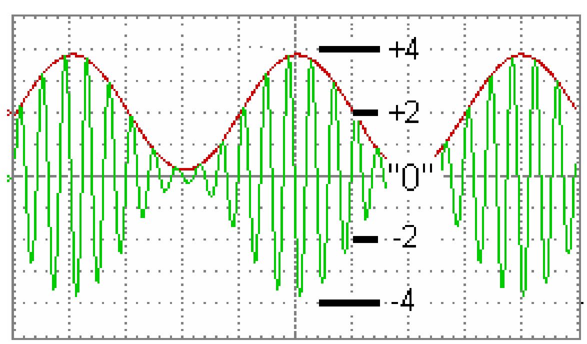
At 100% modulation the signal is made up of the RF carrier at the station's assigned operating frequency and a pair of sidebands corresponding to the audio modulation; each sideband contains 25% of the power of the carrier. That is, the sidebands are 6dB (in voltage amplitude) below that of the carrier when the carrier is modulated to 100%.



When the modulating signal causes the carrier to be 100% modulated the amplitude of the carrier is reduced to zero during the negative excursions of the audio waveform, and during positive peaks it reaches twice the carrier-only value. The resulting modulated RF carrier looks like this.



Therefore at 100% modulation the RF carrier will be swinging between zero and twice the carrier value as shown. 100% modulation is shown here as the waveform reaching +/-4 units in amplitude where the un-modulated carrier by itself would just be +/- 2 units.



We have just seen that at 100% modulation the peak modulated RF carrier voltage (**E**) is *twice* the carrier-only value (hang in there – this is important!). Since the value of load resistance is fixed (let's use 50 ohms in this example) the RF *current* (**I**) into that load resistance must also be *twice* the carrier-only value.

According to Ohm's law then, the RF power (**P**) at 100% modulation must be *four times* that of the un-modulated carrier. The following two examples show how this applies to our custom 10 watt AM lab transmitter when using Mr. Ohm's familiar relationship:

$$P = E \times I$$

Un-modulated Carrier Condition

Carrier Voltage (**E**) = 22.4 Volts
Load Current (**I**) = 0.448 Amperes
Load Power (**P**) = 10 Watts

100% Modulated Carrier Condition

Peak Carrier Voltage (**E**) = 44.8 Volts
Peak Load Current (**I**) = 0.896 Amperes
Peak Load Power (**P**) = 40 Watts

This "4-times carrier power" condition exists during the positive peaks of the modulated envelope which is why it is referred to as *Peak Envelope Power (PEP)*.

By way of the above example the custom 'low power' 10 watt AM transmitter used in the Vorsis design lab must deliver *40 Watts* of *Peak Envelope Power* to its dummy load in order to achieve 100% modulation! AM is quite a bit more complicated than just 'making some carrier power'!

Custom 10 Watt AM Transmitter

Putting More Power into the Sidebands

In the previous discussion we saw that at 100% modulation only 25% of the power goes into each sideband. Since it is the *sidebands* and not the more powerful carrier that carries information to a distant receiver, in order to gain coverage area without increasing the transmitter's licensed carrier power, it is the power in the *sidebands* that must be increased. This is where modulation above 100% can benefit an AM signal's coverage.

> *Note that it is unacceptable to modulate an AM transmitter beyond 100% on negative peaks because doing so cuts off the RF carrier during those negative peaks and this creates spurious signals that will interfere with adjacent stations.*

Fortunately the same restriction does not apply to positive peaks, which may be greater than 100% *as long as the transmitter is linear at the desired positive modulation level* and *the components in the transmitter and antenna system are capable of handling the increased voltages and currents*.

The *extra* sideband power created through modulating above 100% in the positive direction comes from the transmitter's power supply via the modulator and RF final amplifier, noting that extra RF *input drive* must also be available to the RF final power amplifier to satisfy *its* own requirement for higher RF drive during positive modulation.

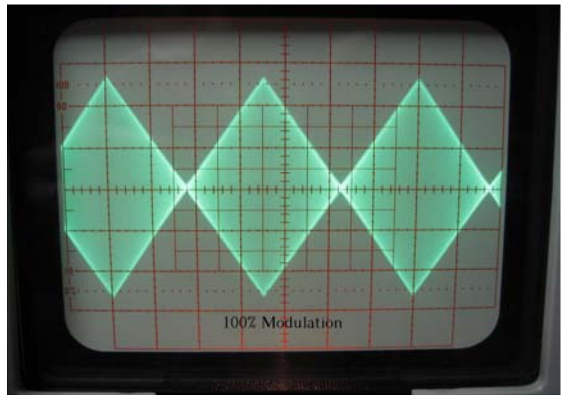
Certain countries (like the United States) impose a limit on the maximum positive modulation percentage. In the US a "+125% maximum" regulation was put into place as an interference management incentive to "discourage" the operation of AM transmitters beyond their linear modulation capabilities – the author remembers a short period during his early career when there *was* no limit on positive modulation. We had some fun back then….

The reader is advised to be aware of his transmitter's modulation capabilities and always operate it within its limitations. Most transmitter manufacturers can provide advice on the modulation characteristics of their transmitters. Note however that "on paper" specifications may be adversely affected by real-world things such as poor AC line voltage regulation and impedance bandwidth issues in the AM antenna system, particularly when modulating with aggressive pre-emphasis in the audio processor.

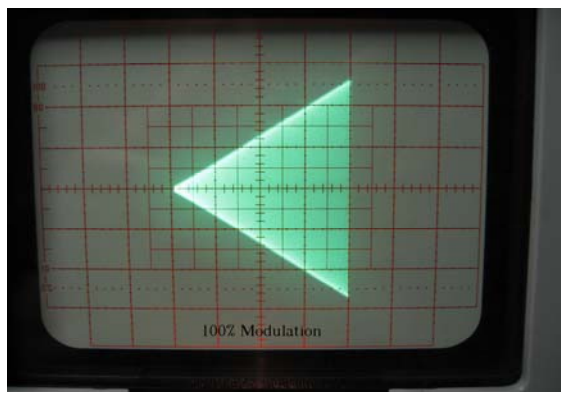
The Holy Grail - Modulation Linearity

Other than capable audio processing and a good antenna system nothing is more important to good AM sound than the linearity of the transmitter. Good linearity means low distortion – THD (Total Harmonic Distortion), IMD (Intermodulation Distortion) and TIM (Transient Intermodulation Distortion) must all be minimized in order to put truly *great* sound on the air.

On the right is an oscilloscope photograph of an AM transmitter modulated to 100% with a very high-quality triangle waveform. Note the transmitter's very high linearity – the triangle waveform's sides are very straight with no signs of bowing, rounding off of the peaks, or other distortions.



In the next photo is the same modulation level displayed using the familiar 'trapezoidal' method. This modulation display is created by applying the RF carrier to the oscilloscope's vertical amplifier and the modulating audio to the horizontal amplifier with the 'scope operating in X-Y mode. Note again the extremely high linearity of this transmitter.



The near-perfect linearity shown in the above photos demonstrates the kind of audio performance required to provide high modulation levels and high signal quality simultaneously.

The custom-built low power transmitter that was used to test the AM-10HD and create the photos for this paper has better than 0.05% THD, IMD, and TIM at 100% modulation – this level of performance was not trivial to achieve, even at the low RF power levels utilized! It is probably <u>unreasonable</u> to expect this level of audio performance in a broadcast transmitter that must operate at far higher power levels. However, the important point is that the lower the transmitter's own distortions, the better the on air sound will be!

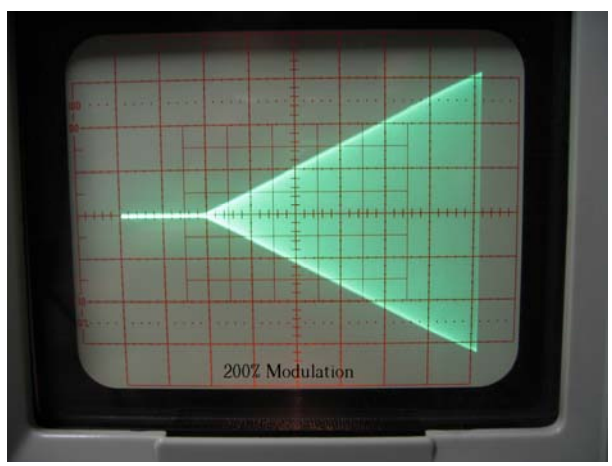
It's a Tough Crowd Above 100% – What Does It Really Take?

It has been customary in the design of AM processors to provide positive modulation capability of about 150%. When we designed the ten-band limiter for the AM-10HD we invented a new method for managing the 'symmetry' domain that allows up to 200% positive modulation without simply clipping the negative peaks. The result is 'natural', effortless positive modulation up to 200%... if your transmitter can do it.

We would be remiss if we didn't mention that 200% positive modulation requires a transmitter with 6dB of **power** headroom *above* 100% modulation while also remaining highly linear to prevent distortion products from creating interference to other stations. Clean modulation *is* the holy grail of *great* AM sound.

The only AM 'transmitter' that we're aware of that *linearly* achieves 200% modulation is the 10 Watt High Linearity AM Signal Generator that the author designed and built specifically for testing AM-10HD's modulation capabilities in our Vorsis lab. It was the signal generator used while capturing the oscilloscope photographs for this paper.

In the photograph on the right the AM generator is intentionally driven 6dB beyond 100% modulation where it develops 160 watts Peak Envelope Power at 740 kHz and 200% positive modulation.



*(A 50kW broadcast transmitter would need to deliver **800kW** Peak Envelope Power to the antenna in order to modulate like this!)*

Note: We needed a virtually perfect AM transmitter to use in combination with various consumer-grade receivers for preliminary on-air testing of the AM-10HD and for creating and tuning some of its Factory Presets. By being a transparent 'reference' transmitter the AM signal generator allowed us to evaluate the AM-10HD without being constrained by the unknown characteristics of an AM broadcast transmitter operating into its usual less-than-ideal load.

Let's return for a moment to a previous statement:

"When we designed the ten-band limiter for the AM-10HD we invented a new method for managing the 'symmetry' domain that allows up to 200% positive modulation <u>without</u> simply clipping the negative peaks."

What does this mean to an AM station? It means that *any* degree of positive modulation may be achieved (within the limits of the transmitter) and without relying, as most other AM audio processors do, on brute-force clipping of negative modulation peaks in order to create 'false' asymmetry.

This also means that because the AM-10HD's asymmetry occurs 'naturally', and is adjustable from 100% to 200% without any performance tradeoffs it is both cleaner on the air and kinder to the transmission system because there is no hard clipping of the negative peaks used to create it.

Always Ten Limiter Bands…
and at Any Desired Bandwidth!

When our Vorsis team gathered around the big white board and a (not-giant-enough) pizza to design the AM-10HD product we had two goals that, if we could achieve them, would make it a "killer AM processor":

First, we wanted *clean* and *unrestricted* positive modulation without relying on the deep negative peak clipping that most AM processors must use to "create" asymmetry. We achieved that goal by doing some new and special things inside the ten band limiter's algorithms.

Second, we wanted to create a ten-band AM processor that, regardless of the cutoff frequency of its output low pass filter, was always equipped with ten-bands of spectral control in the limiter section. We achieved this by borrowing some underlying technologies used in the twin 31-band limiters in our AP2000 FM Flagship Processor.

As the user selects different output low pass filters in the AM-10HD the operating frequencies of the ten-band limiter's filter bank are <u>recalculated in real time</u> - regardless of the low pass filter restriction dialed in by the user, *<u>ten bands</u>* of spectral limiting are always available.

Allow us to explain, using the following question as an example, why we felt this was an important, ‘must have’ feature in a high-end AM audio processor:

Q. *As the output bandwidth is dialed back in conventional AM processors, what happens to the processing work that was done by the processor’s upper bands of processing that now fall above the low pass filter’s cutoff frequency?*

A. That processing power is thrown away… gone for good.

Why does this happen?

Consider a five band AM processor designed for processing audio frequencies up to 10 kHz - its bands are spaced out across the audio spectrum up to the processor’s 10 kHz bandwidth limit.

Now readjust that processor’s output low pass filter from 10 kHz down to 5 kHz; not an unusual setting. What just happened to the *program energy* that was being processed by the limiter bands that were handling program energy above 5 kHz?

It goes away just as it should. But what else goes away?

*Half of the processing capability! A*t a low pass filter setting of 5 kHz that five band AM processor has now become about a 3-band processor at most! It’s certainly no longer the five-band processor that you paid for!

All other AM audio processors behave like this, even our low cost VP8 when operating in its AM mode! Unfortunately as AM bandwidth is reduced and the upper bands ‘go away’ it becomes increasingly challenging to create a competitive on-air sound. The upper processing bands are simply no longer available to be used.

If it is more difficult to provide a competitive on-air sound as the AM bandwidth is reduced, wouldn’t it be better to have more processing bands available to do this work and not less?

Unequivocally the answer is yes! By recalculating the AM-10HD’s ten-band filter bank ‘on the fly’ so that all ten bands are always available it can maintain a competitive air sound in *any* desired bandwidth environment.

Ten bands and no swishing!

In the 1970's multiband processing really started to take off. By 1975 one company had introduced an AM audio processor with eight bands. This was a lot of bands and involved a lot of parts because back then everything was done with discrete transistors and early operational amplifiers (opamps).

Because computer power was not yet affordable for mere mortals, audio crossover networks were manually calculated and then tuned by ear. The result was a design that was 'functional' but certainly not of the quality achievable with the mathematically perfect crossovers we can build today using high-end design and modeling tools and DSP.

Because of its less than ideal band-to-band phase behavior (and in spite of its quite-capable designer!) this eight band processor and its successor became known as the 'Swish-a-Matics'. Even today, some 33 years later, those in the broadcast industry long enough to remember those early products sometimes still believe that *any* audio processor having more than five or six bands *must* certainly be a 'Swish-a-Matic' too.

That was then…

1975

This is now!

2008

Fortunately we don't have the same limitations today that we had back in 1975! In fact, eight bands is nothing now – we have a limiter with 31 bands in our high-end FM processor and *it* doesn't 'swish'!

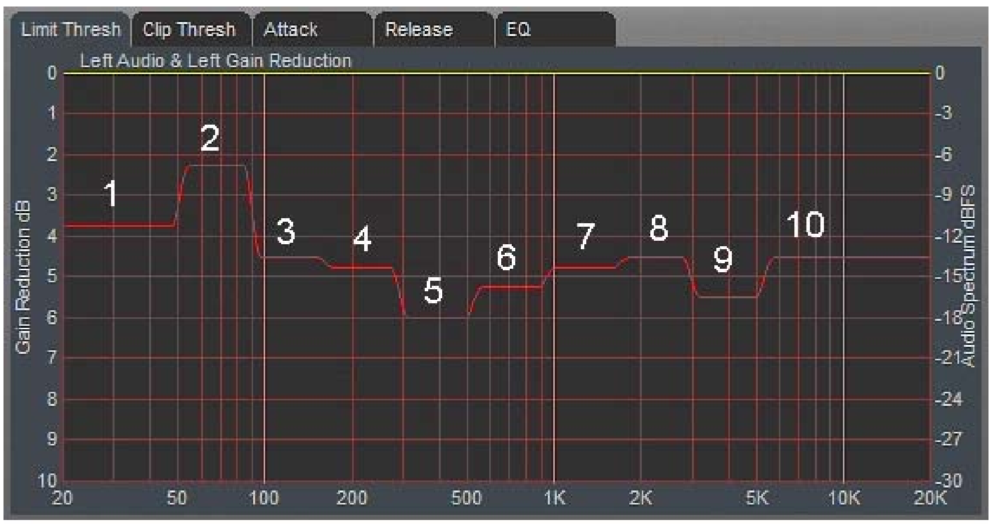
Not only does the Vorsis AM-10HD retain all ten bands of spectral control in its final limiter no matter what the bandwidth setting is, but because of its very careful crossover design, it simply can't, 'swish'.

The AM-10HD's five-band AGC crossover frequencies can be tuned to optimize the processor's performance for any low pass filter setting and program format, fully complementing the ten-band limiter's own automatic reconfiguration.

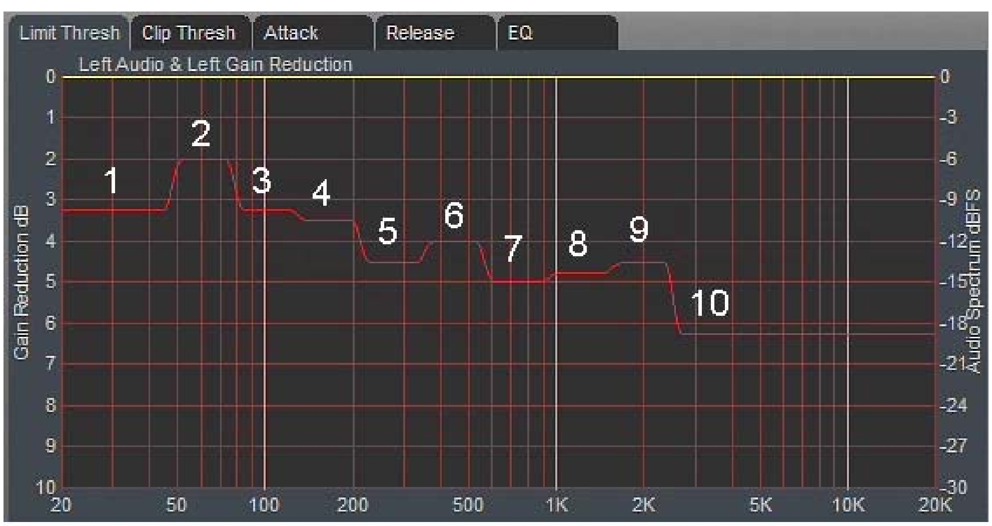
The following screenshots are from the AM-10HD's GUI showing the ten-band spectral limiter screen while operating first at its highest, and then at its lowest, low pass filter settings.

Note that as the output bandwidth is reduced the ten-band limiter's filter bank automatically *recalculates* its center frequencies so that there are *always* ten bands of spectral limiting available.

Count the bands!



NRSC Low Pass Filter Setting (10kHz)



4.5kHz Low Pass Filter Setting

Spectral Shaping For Better AM Sound

The top band of the five-band AGC crossover may be set as low as 2.52 kHz in order to optimize the on-air sound for very restrictive low pass frequency settings. The crossover frequencies of the other four bands may be skewed as desired - there are always five bands of AGC/Compressor available at any user chosen bandwidth. No other AM audio processor has this flexibility and level of processing power.

There are three important advantages with our new AM processing scheme:

1. Clean positive modulation adjustable between 100% and 200% for *loud and clean* AM dial dominance.

2. Spectral shaping and precision of loudness control that is *impossible* to achieve with *any* other AM audio processor;

3. Fully customizable pre-emphasis to more closely complement the restricted high frequency response of *<u>today's</u>* consumer-grade narrow-bandwidth receivers.

Speaking of Pre-emphasis…

In the United States the National Radio Systems Committee (NRSC) *recommended* that a specific pre-emphasis curve be used for AM – thankfully it is *only* a recommendation.

Vorsis team members - many are former broadcast engineers with decades of real-world experience - believe that AM stations should be free to create *any* pre-emphasis curve that best complements their programming format *<u>as long as it does not create interference</u>*. This is why the AM-10HD has such highly specialized spectral energy shaping and management technology.

When it was first implemented the NRSC pre-emphasis curve was a good tradeoff between existing receiver behavior and laws of physics. It is not very suitable anymore for today's narrow bandwidth consumer radios however, and therefore we cannot recommend using NRSC pre-emphasis by itself. That said, we *do* firmly recommend utilizing one of the <u>very tight</u> low pass filters available in the AM-10HD's output in order to restrict the transmitted bandwidth to reduce the likelihood of adjacent channel interference.

NRSC Pre-emphasis

The graphic below is the original NRSC recommended pre-emphasis for AM stations. Note that the response is up by 10dB at 10 kHz and that at midrange frequencies where typical consumer receivers now roll off the response is boosted by 5dB or less. This is not enough equalization to deliver good sound on a typical consumer radio.

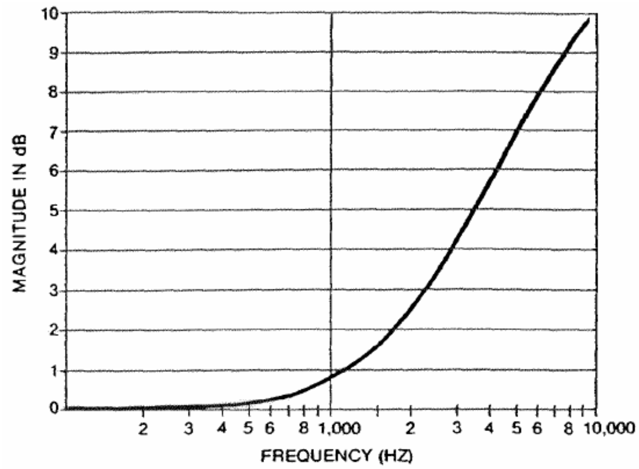
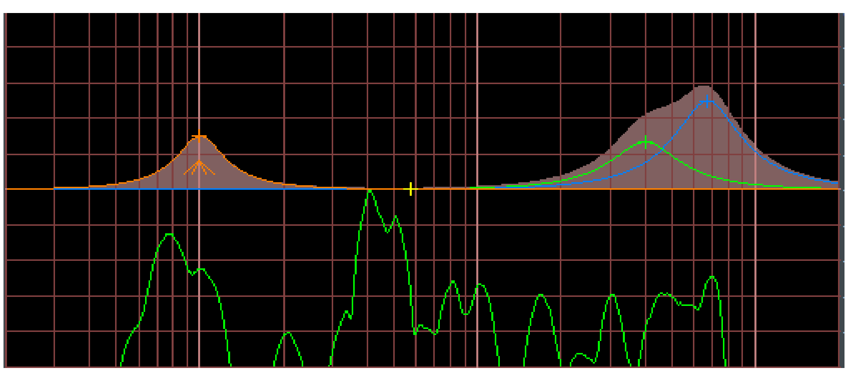


Figure 1. Modified 75μs AM Standard Preemphasis Curve

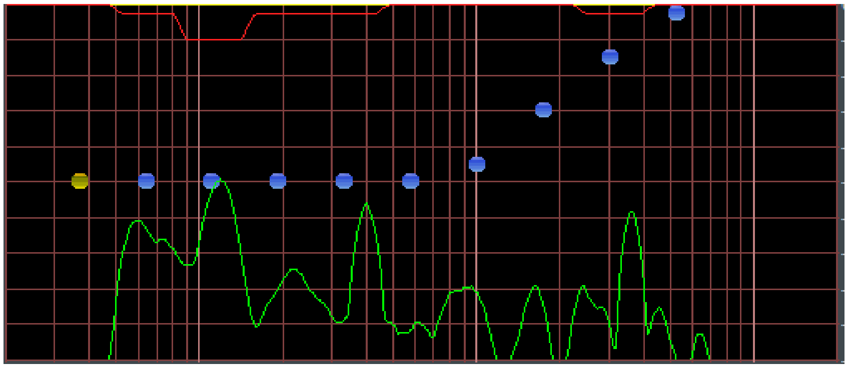
So what do we do to fix this? We create a custom pre-emphasis curve that better complements the audio response of today's receivers!

Creating 'non-standard' Pre-emphasis

Below are screen shots of the pre-AGC parametric equalizer and ten-band limiter thresholds from one of our Factory Presets. The shaded areas show the combined frequency response of two high frequency equalizer sections 'stacked' to create an equalization shape that is unachievable with simplistic peaking or shelving equalizers.



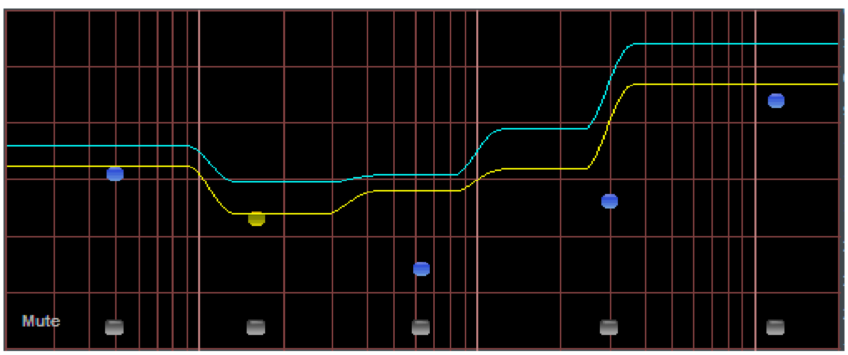
Pre-AGC/Compressor Parametric Equalization



Ten Band Limiter Thresholds

For this 7.5 kHz preset we used a combination of NRSC pre-emphasis, some additional spectral shaping in the pre-AGC parametric equalizer, and staggered spectral limiter thresholds in the ten band section. This creates a bright and airy sound on a typical consumer-grade AM radios *without* generating tuning difficulties on analog radios, excessive stridency, or undesired out of band interference.

Next, look at how we adjusted the AGC/Compressor thresholds to 'pre-load' the audio spectrum ahead of the ten band spectral limiter.



AGC/Compressor Thresholds Screen
(blue dots are AGC band thresholds)

By manipulating the AGC/Compressor thresholds we're able to create a sloped spectral energy curve at the input of the ten band limiter that, along with its own specialized tuning and the parametric equalization applied earlier in the processing, delivers a bright and airy sound on a typical consumer-grade AM receiver. In fact, the name we gave this particular factory preset is "Bright_Dense_7dot5kHz".

Next, observe how we've adjusted the 48dB/Octave (yes, they are 8^{th} order!) AGC/Compressor crossover frequencies in that preset...

AGC/Compressor Crossover Frequencies

Note the low to low mid crossover setting of 108Hz which allows deep bass to be heard on receivers capable of reproducing those frequencies while also keeping 'mud' out of receivers that simply can't produce them.

The low mid to mid crossover has been set to 334Hz and the mid to high-mid crossover to 972Hz which helps concentrate the midrange frequencies and process them in a way that increases intelligibility on average AM receivers.

The mid high to high band crossover has been set to 2.90 kHz which was done to allow band five to process energy for receivers whose frequency response extends above 2.90kHz. Receivers that do not reproduce frequencies above 2-3 kHz benefit most from the combined processing of the first four bands.

Like most of the AM-10HD Factory presets, "Bright_Dense_7dot5kHz" was tuned to make the ten band limiter's most important contribution be 'short-term spectral' control. This tuning works in concert with the dynamics of the multiband AGC/Compressor to keep the overall sound of the station very refined and consistent as the station's program elements change.

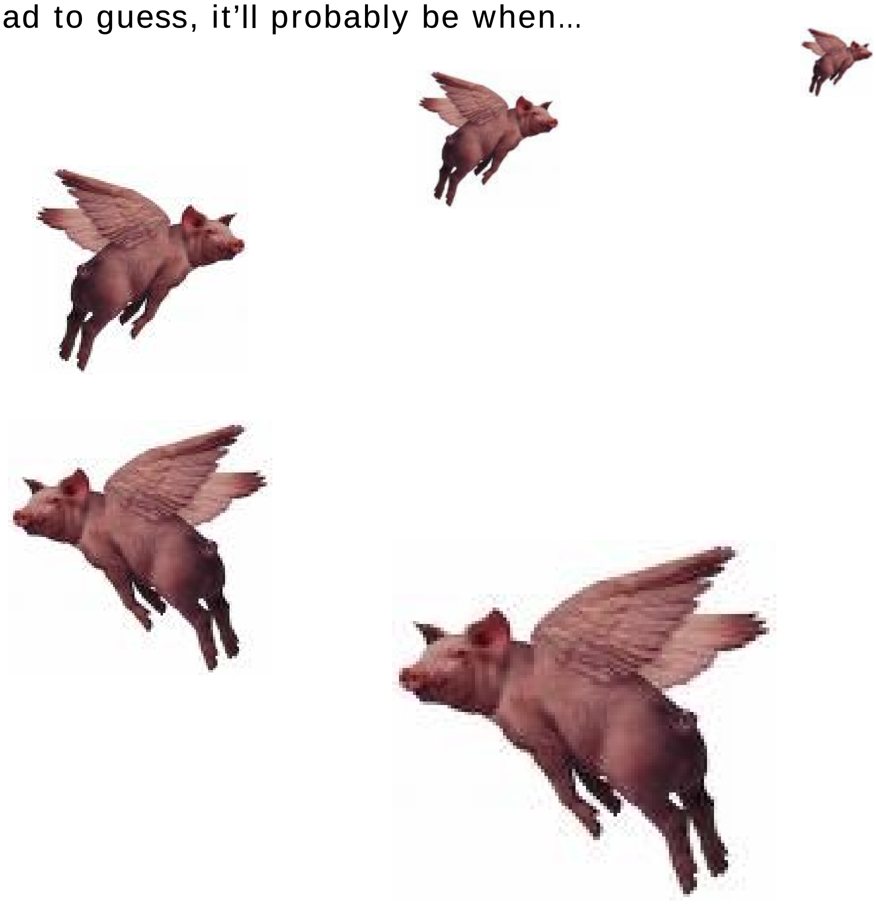
Summary

With the flexibility to adjust the AM-10HD AGC crossover frequencies to complement the settings in the ten band spectral limiter and low pass filter we can squeeze very nice sounding audio from today's very narrow bandwidth consumer radios, and do it without generating unnecessary and fatiguing processing-related artifacts.

Unlike other AM audio processors the AM-10HD is not relying on simple equalization or fixed high-frequency pre-emphasis to generate a complementary response curve for the AM receivers that existed back when the original NRSC pre-emphasis/de-emphasis was adopted in January of 1987 - over 20 years ago!

Rather, the AM-10HD operates as a system to tailor the spectral energy in the station's program audio to enhance how well the station covers its market and how faithfully consumer receivers of today reproduce it. The result is full modulation of the transmitter and high perceived loudness *and* quality at the listener's receiver, without generating strange spectral oddities (like swishing!) or listener-fatigue-causing harshness.

The trend for some years now has been for manufacturers to build ever-narrower consumer AM radios. We don't know for sure when better AM receivers, ones with audio frequency response that extends above 5 or 6, or maybe even 7 or 8 kHz might be available once again, but if we had to guess, it'll probably be when...



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