Comments Regarding "A Method to Improve Conventional FM Stereo Performance"

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Recently a method to improve the performance of FM stereo by replacing the conventional method of broadcasting a double side band (DSB) suppressed carrier stereo sub carrier with that of a single side band (SSB) suppressed carrier stereo sub carrier has been proposed. This paper develops a comparison of the effects on synchronous AM noise generation due to monaural, normal DSB stereo and the proposed SSB stereo approach. There is also a discussion of SSB techniques and some of the challenges to applying this technology to FM broadcasting.

Introduction

Since 1961 North American broadcasters and many broadcasters from around the world have been using the FM stereo system that was selected and mandated by the Federal Communication Commission. This current stereo system which is a hybrid system of those proposed by The General Electric Corporation and Zenith Radio Corporation. The system works by broadcasting a sum of the left and right channels, a pilot tone of 19 kHz and a double sideband suppressed carrier sub carrier that contains the difference of the two stereo channels. The L+R information can be received by conventional FM sets without stereo decoding circuitry whereby existing FM sets were not made obsolete. Newer sets containing the necessary circuitry detect the pilot tone and use it to synchronously detect the DSB carrier providing a demodulated output of the stereo difference information (L-R). The L+R and L-R information are algebraically added and subtracted (L+R) + (L-R) = 2L, (L+R) – (L-R) = 2R thus yielding the recovered left and right channels.

The encoding and decoding of the L-R information can be expressed trigonometrically by use of the trigonometric cosine multiplication identity:

cos u cos v = ½ (cos(u+v) + cos(u-v)) $\qquad\qquad$ eq. 1

Let $\omega_c t = u$ where ω_c is the radian carrier frequency

$\qquad$ $\omega_m t = v$ where ω_m is the radian modulating frequency

$F(t) = \cos \omega_c t \cos \omega_m t = \frac{1}{2} [\cos(\omega_c + \omega_m)t + \cos(\omega_c - \omega_m)t]$ $\qquad$ eq. 2

The expression to the right of the equal sign above is the expression for the double side band suppressed carrier signal. Note that there are no D.C. terms in the above expression which means that there is no carrier without modulating component thus providing the desired DSB suppressed carrier signal.

To recover the modulation component at detection the same multiplication operation is performed on the DSB wave by multiplying cos ω_ct (ω_c= 38 kHz carrier in this case) times the right hand side of equation 2:

½ cos ω_ct [cos(ω_c + ω_m)t + cos(ω_c – ω_m)t] =

½[cos ω_mt + cos($2\omega_c$–ω_m)t]   eq. 3

½ cos ω_mt is the recovered modulation the other term is a second harmonic and is filtered out leaving the modulation component.

Is it possible to replace the DSB sub carrier with SSB and maintain compatibility? The answer is yes. Again using trigonometry we can show this by use of an additional identity:

sin u sin v = ½ [cos(u–v) – cos(u+v)]   eq. 4

Substituting the same terms for u and v as in eq. 1

F'(t) = sin ω_ct sin ω_mt = ½ [cos(ω_c – ω_m)t – cos(ω_c – ω_m)t]   eq. 5

F(t) = cos ω_ct cos ω_mt = ½ [cos(ω_c + ω_m)t + cos(ω_c – ω_m)t]   eq. 6

To produce a lower side band suppressed carrier the two functions are added

F'(t) + F(t) = ½ cos(ω_c–ω_m)t   eq. 7

Eq. 7 is equal to eq. 3 after filtering thus the same information is contained in the DSB and SSB case. Of course upper side band could be produced by subtracting the two functions.

Existing stereo detectors will be able to decode either type of stereo sub carrier as long as deviation of the SSB sub carrier is equivalent to the deviation of the DSB sub carrier which requires a boost of 6 dB of injection level of the SSB sub carrier. This way equivalent stereo decoding occurs. An interesting trait of SSB decoding is that the strict phase coherence necessary for DSB decoding is not the same for SSB. For the DSB case the phase of the reinserted carrier and side bands must be the same for maximum output from the detector. As the phase of the reinserted carrier and sidebands vary from 0 to 90 degrees the output of the detector falls to zero when the carrier/side band relationship approaches quadrature or 90 degrees. The SSB case does not suffer from this condition and full detector output occurs even with a quadrature relationship between side band and carrier.

By use of the trigonometric identity: s**in u cos v = ½ [sin(u+v) – sin(u-v)]**
Where u = (ω_c – ω_m)t (lower side band component), v = ω_ct (reinserted carrier)

$F(t) = \frac{1}{2}\,[\sin(\omega_c{-}\omega_m + \omega_c\,)t - \sin(\omega_c{-}\omega_m{-}\omega_c)t]$

$F(t) = \frac{1}{2}\,[\sin(2\omega_c{-}\omega_m)t - \sin\,\omega_m t]$

The left half of the expression to the right of the equal sign is a second harmonic component which is removed by low pass filtering and the right side of the expression is the detected audio output phase shifted by 90 degrees of the carrier frequency. For the DSB case using the same identity yields:

$u = (\omega_c - \omega_m)t + (\omega_c{+}\omega_m)t\ = 2\omega_c t$ (DSB carrier)
$v = \ \omega_c t$ (reinserted carrier)

$F(t) = \frac{1}{2}[\sin(2\omega_c + \omega_c)t - \sin(2\omega_c - \omega_c)t]$

$F(t) = \frac{1}{2}[\sin\,3\omega_c t - \sin\,\omega_c t]$

The above expression lacks an ω_m component which is the modulation component, therefore the detected output is zero.

The mathematical treatment of SSB generation can be realized by a variety of methods including the filter method where generation of a DSB wave and filtering the unwanted side band, the phasing method whereby two balanced modulators fed with quadrature modulating and carrier functions and adding or subtracting the result to produce the desired side band output and a third method known as the Weaver method which uses a combination of techniques to generate the same result. The mathematics of all three methods develops the same result.

At first glance it would appear that the SSB sub carrier would have some advantages. Clearly there is a reduction of the amount of base band spectrum utilized as the SSB carrier only requires 15 kHz spectrum where the DSB case requires 30 kHz. There is a reduction of the complexity of FM side bands generated by the SSB case due to the fact that side bands would extend out from the carrier starting at 38 kHz instead of 53 kHz so there is a slight reduction in band width of the emitted FM signal. In a less than perfect transmission system where non linearities can cause crosstalk between stereo and SCA channels there may be a slight reduction in that type of interference. For the proposed SSB technique there would be little reduction of the FM channel due to the fact that +/- 75 kHz deviation is preserved. Deviation dictates FM channel bandwidth.

There are at least two challenges with utilizing an SSB sub carrier as proposed for use in FM stereo. The first has to do with the relationship of the derivative of the modulating function introduced to the SSB modulator and the carrier amplitude. There is a direct relationship to the derivative or rate of change of the modulating function and carrier power. As the derivative of the modulating function tends to infinity so does the carrier power. An example of a high derivative function is a square wave. The leading and trailing edges of this type of waveform have a theoretical derivative of +/- infinity. Slew

limitations in any system will tend to cause the derivative to be something less than infinity but highly transient modulation components will tend to cause difficulty in controlling overall modulation levels of the SSB envelope and therefore the FM carrier deviation.. This means that highly transient wave shapes such as those produced by audio processing, audio clipping devices and even plain speech can cause SSB carrier levels to peak to a greater degree than the equivalent AM or DSB cases. The transient problem inherent in the SSB case may be able to be addressed with some processing of the system but introduces complexity to the stereo generator.
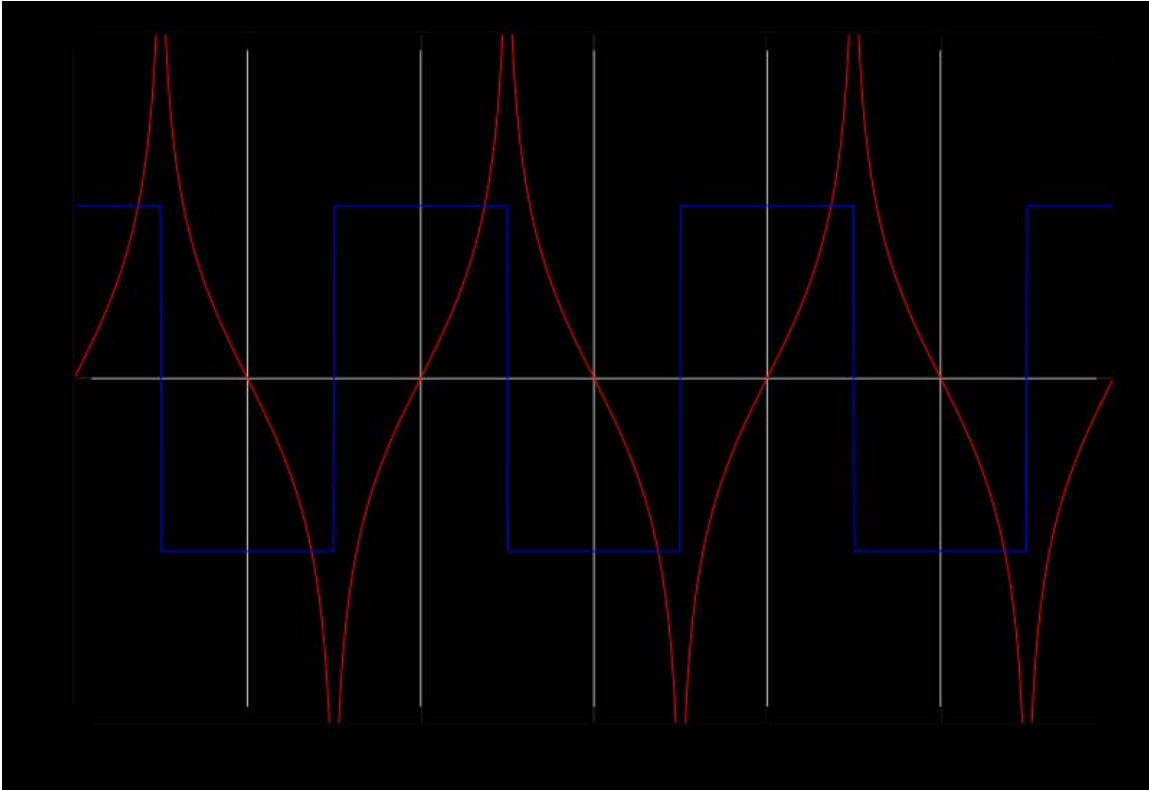
The above illustration is that of the Hilbert transform in red of the square wave in blue. Note the vertical transitions of the square wave coincide with the Hilbert transform as it tends toward negative and positive infinity.

The Hilbert transform for a rectangular function such as the above square wave is of the form:

$$F(t) = 1/\pi \ln \left| (t+1/2)/(t-1/2) \right|$$

For trigonometric functions the Hilbert transform takes the forms:

F(t) = sin(t), Hilbert transform of F(t) = -cos(t)

F(t) = cos(t), Hilbert transform of F(t) = sin(t)

For the sine and cosine functions it can be seen there is a phase shift of 90 degrees from one to the other. In the case of the rectangular wave in addition to the phase shift there are values of t that in the transform tend toward infinity which when multiplied by the carrier function such as in an SSB modulator will force the carrier amplitude to +/- ∞. Unless the modulating function is of a strictly sinusoidal type or processed, peak to average carrier ratio will exceed one. If this is then applied to an FM transmission system the deviation of the FM carrier will follow the peak to average ratio of the SSB wave. Due to this fact peak deviation of the FM transmitter will be difficult to control unless overall modulation deviation of the FM transmitter is kept well below of the peak to average carrier ratio of the SSB modulator. This will cause a loss of apparent signal to noise ratio of the FM transmitter.

A claim has been made about the SSB technique that it will reduce multipath distortion of the received FM signal. First of all I believe there is much use of the term "multipath" that in the author's opinion is not a correct. Multipath is simply the multiple paths that a signal can take before getting to the receiver due to reflections caused by objects such as architectural structures and terrain. The vector summation of these signals at the receiver may cause noise and distortion due to a set of variables. In a wide band FM system multipath distortion is complicated by the modulation component. In a CW case with no modulation the amplitude of the resultant vector is strictly governed by the relative amplitudes of the reflections, and their phase relationship which has to do with the time delay of the reflections. In an FM case the modulation component will cause the phase relationship of the reflections to change at the modulation rate which can cause a rise and fall of the resultant vector. This effect is called synchronous amplitude modulation. So for the FM case there are several variables that can effect signal present at the receiver including the number of reflections, their relative amplitudes, their relative phase due to the time delay of the reflections and the modulating component which causes additional incidental phase shift resulting in amplitude modulation of the FM carrier.

The recent proposal utilizing SSB techniques discussed earlier include a claim that incidence of multipath like noise could be reduced in a typical reception scenario if SSB stereo was utilized instead of DSB. It was desired to know whether or not DSB vs. SSB stereo would perform differently when the received signal was that composed of a direct and time delayed signal. To test this hypothesis Dr. Greco and I developed a formula based on work done by Corrington[1] of RCA to graphically display the effect modulation depth, frequency complexity and time delay on a received FM signal. The original work by Corrington at RCA was done before FM stereo had been contemplated and the formula developed was for single tone modulation. We modified this equation to include multi-tone modulation to show the two stereo cases. The formula is an integration of the FM carrier with respect to time taking into account the modulation depth, modulation

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[1]   Corrington, Murlan S. Frequency Modulation Distortion Caused by Multipath Transmission, IRE, December 1945

frequencies and time delay. The integration time was set long enough to display several cycles of the various modulation frequencies. The test case is the simplest in that there are assumed to be two signals arriving at the receiver. More complex situations exist in the field and field testing of such a system before adoption is highly recommended. In our simulation the first term is a direct signal where we fixed the amplitude to 1. The second arrives at the receiver 35 microseconds after the first equating to 6.5 miles which is a typical multipath situation found in many cities and mountainous regions. We set the time delayed amplitude at 0.9 to show near cancellation. Three sets or runs were performed. The first was monaural tones modulating the transmitter to verify Corrington's work. The waveforms shown are the envelope distortion at the input to the limiter of the receiver. Two sets of additional runs were performed at 50 Hz, 1000 Hz, and 15 kHz modulating frequencies for the normal DSB stereo case and the proposed SSB stereo case. Modulation was assumed to be 75 kHz total modulation including 10% pilot injection for the stereo cases. Deviation was adjusted in the SSB case to produce the additional 6 dB injection level necessary to insure compatibility with existing receivers.

The results show that in each case that the waveform starts out in phase and as the carrier is FM modulated that the two waveforms go in and out of phase in synchronization with the modulating function. For the simplest monaural case it can be seen that the FM envelope is modulated in a near sinusoidal manner. For the stereo cases the situation is more complex due to the additional tones modulating the transmitter.

What we set out to verify was the fact that received noise and distortion in a wide band FM system is a function of the following factors:

1. Deviation
2. Time delay
3. Ratio of multiple signals

The generalized equation used for this analysis is:

$$E(t) = \left| Ae^{j\omega_c t + jk \int_0^t V_m(\tau)d\tau} + \sum_{i=1}^N B_i e^{j\omega_c(t-t_i) + jk \int_0^{t-t_i} V_m(\tau)d\tau} \right|$$

E(t) is the received signal at carrier frequency ω_c with amplitude A modulated by $V_m(t)$ using peak deviation sensitivity k (in rads/V/sec) containing Multipath effects due to N reflections of t_i delays and B_i amplitudes.

Figure 1 below duplicates Corrington's work to show 30 Hz modulation tone at 60 kHz deviation. This was done as an exercise to make sure the simulation matched that of the original work and in fact it does. The top figure shows the envelope distortion due to the vector summation and cancellation at the audio rate of 30 Hz. This demonstrates, rather dramatically, the effect of time delay of FM signals. Note that for a condition where no

multipath is present the upper graph would be a straight line with constant amplitude and the lower spectrum plot would have only one line at the carrier frequency. The lower graph is a spectrum plot of the AM component of the resultant vector that would be presented to the limiter in a typical FM receiver. This became a very valuable tool to analyze the various cases as will be seen in later figures. Figures 2-4 show the effect for 50, 1000 and 15000 Hz respectively.
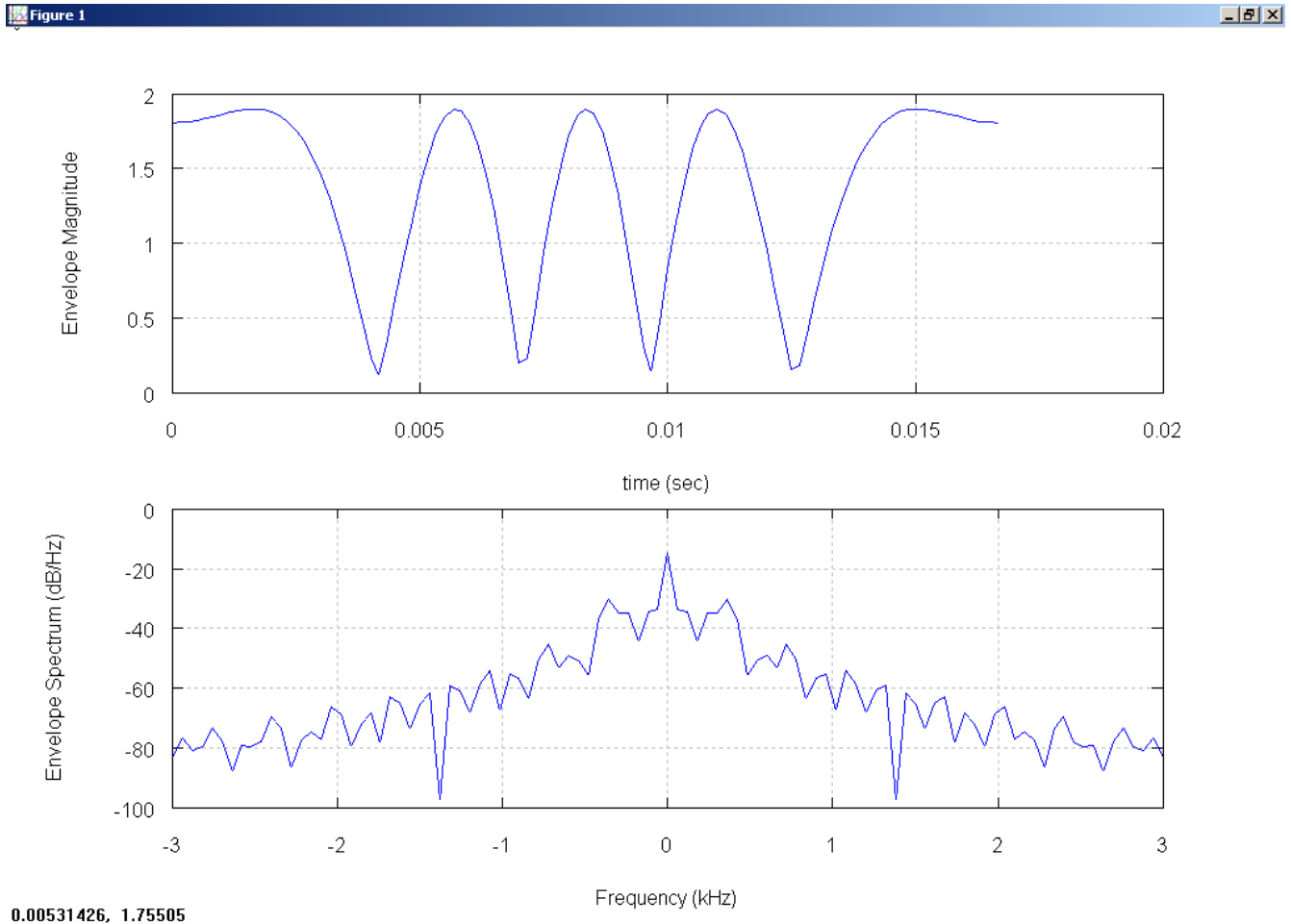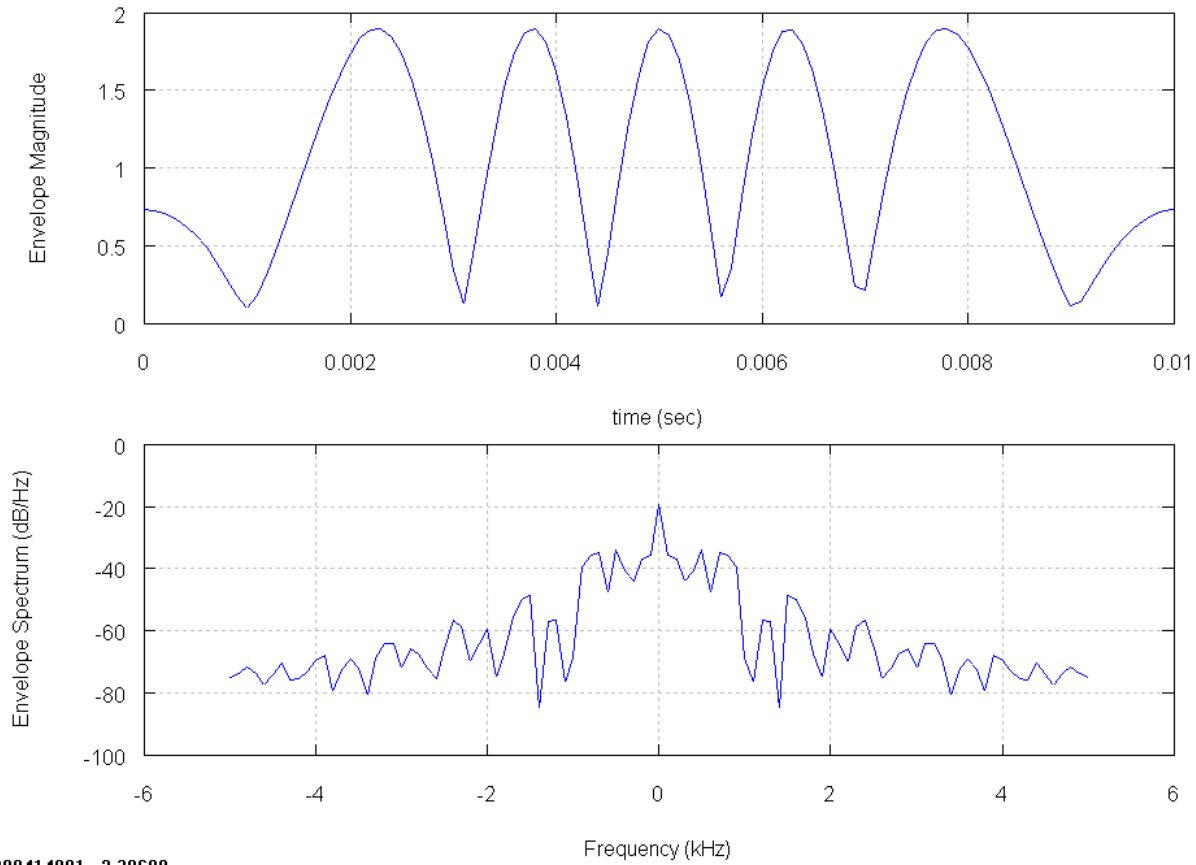

Corrington paper [from Figure 1] (Baseline):
Monaural Case (single tone, Fm = 30 Hz)
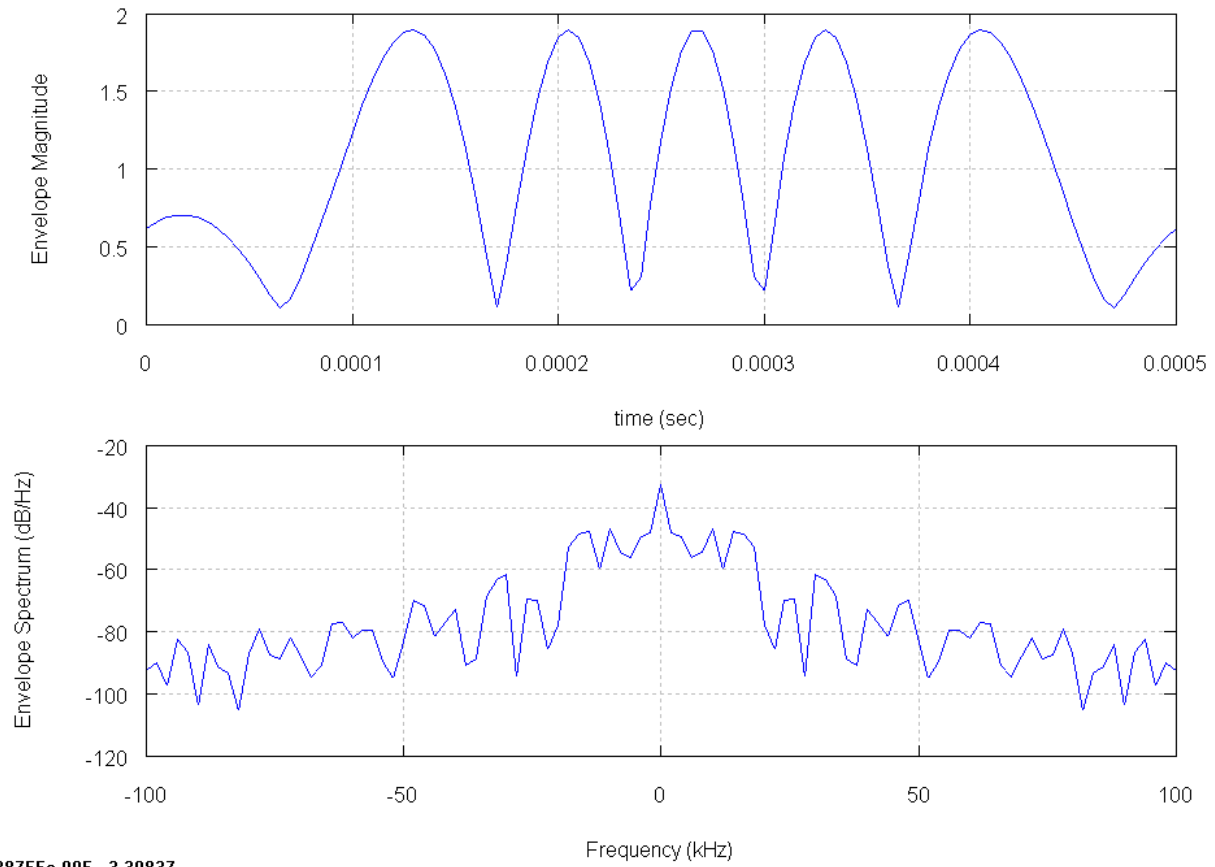Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
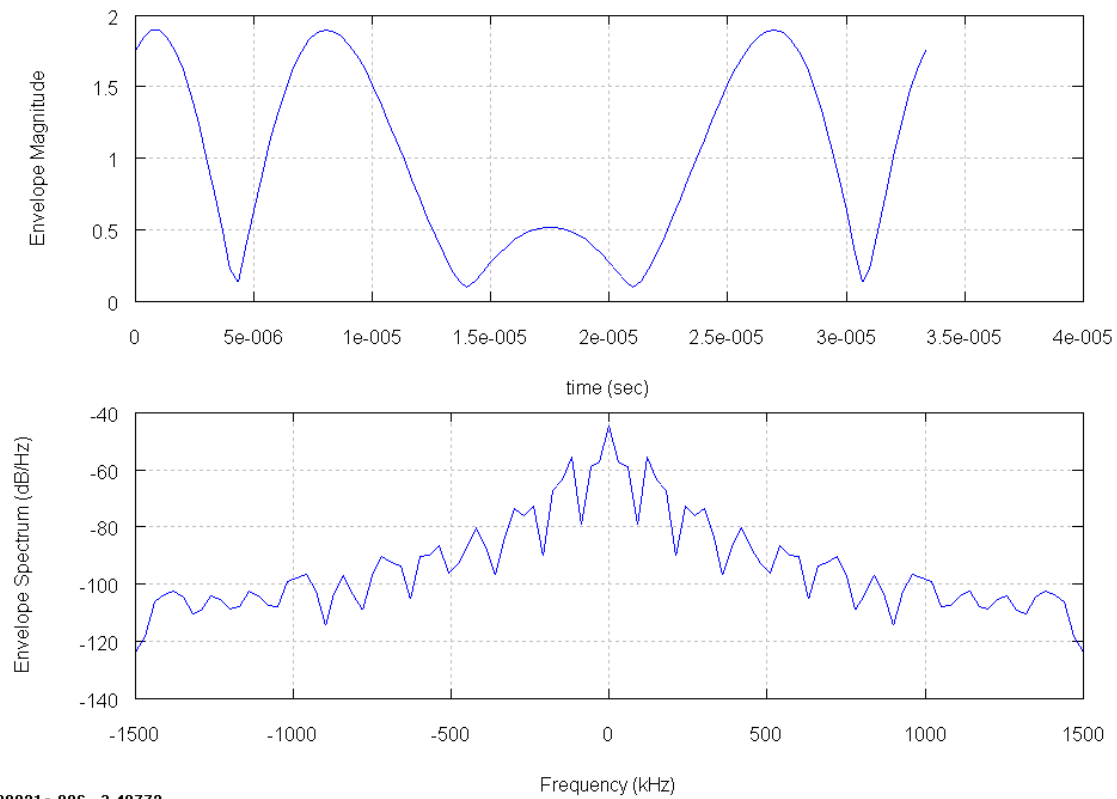Peak Frequency Deviation = 60 kHz

Figure 1

0.000414001, -2.39609

Figure 2 Monaural Case (single tone, Fm = 50 Hz)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
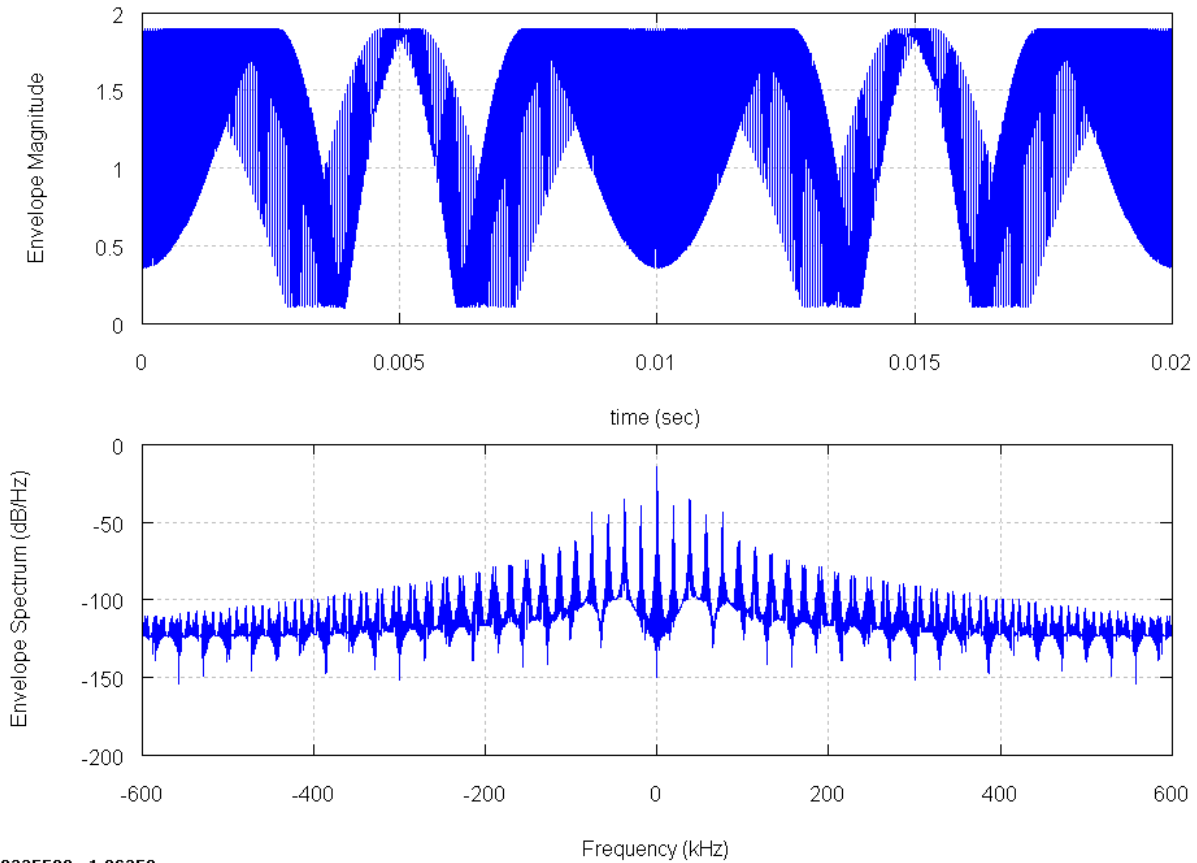Peak Frequency Deviation = 75 kHz

Figure 1

-8.38755e-005, -3.39837

Figure 3 Monaural Case (single tone, Fm = 1000 Hz)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
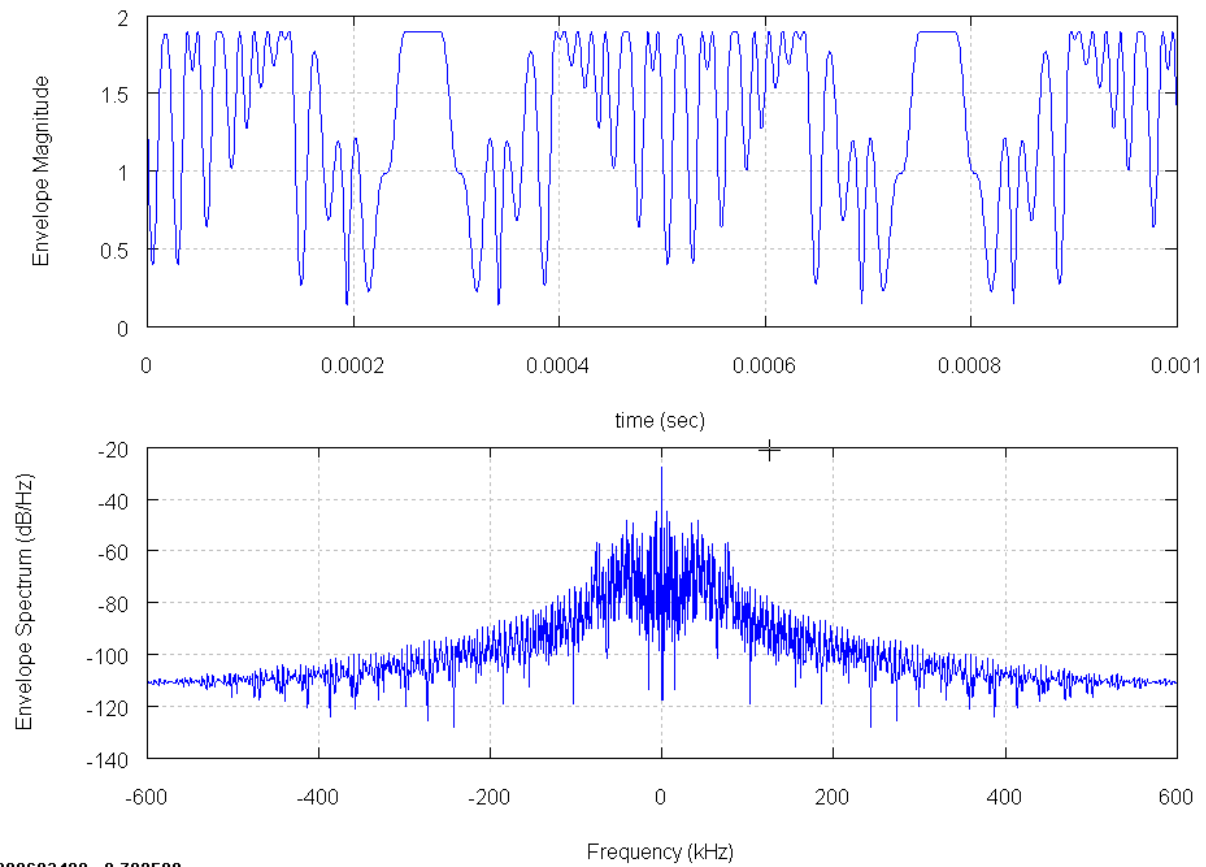Peak Frequency Deviation = 75 kHz

Figure 4 Monaural Case (single tone, Fm = 15000 Hz)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
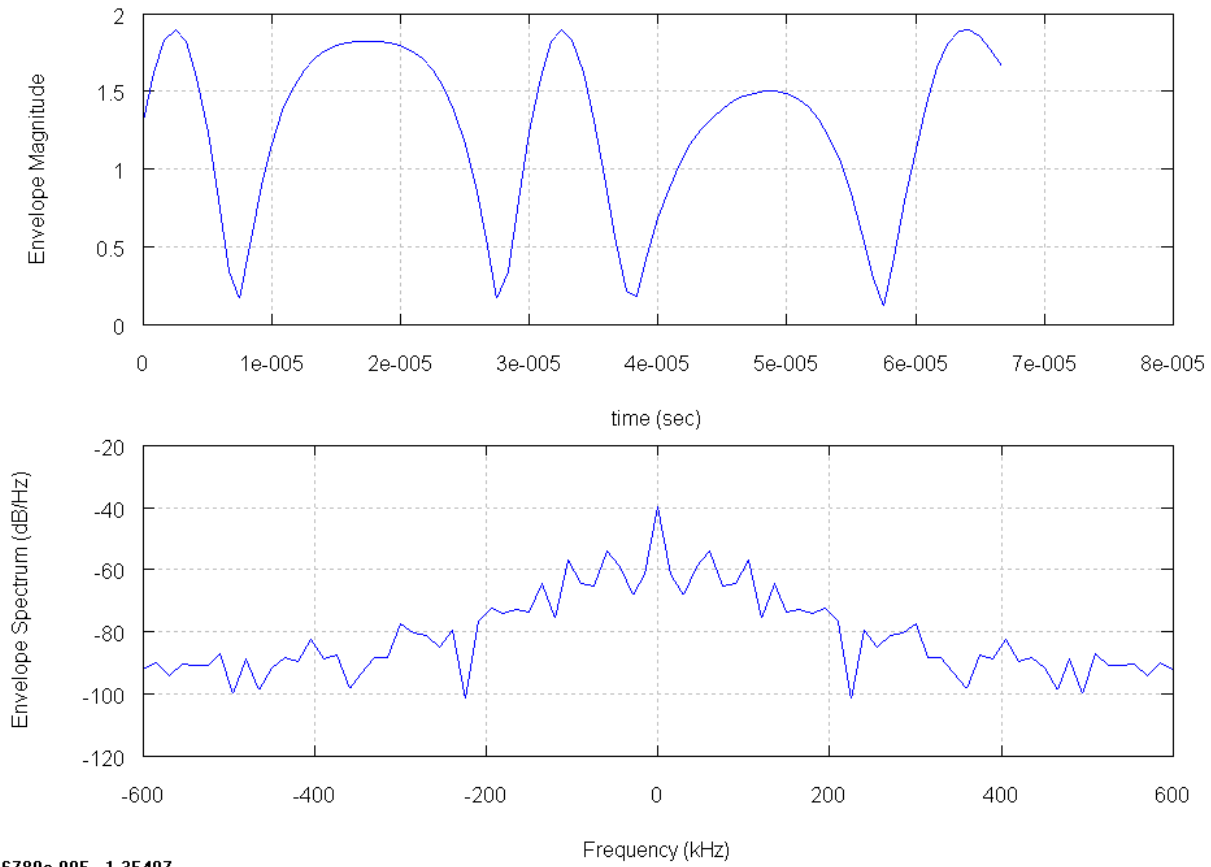Peak Frequency Deviation = 75 kHz

Figure 1

-0.00335502, 1.86352

Figure 5 DSB Stereo Case (single tone, Fm = 50 Hz)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
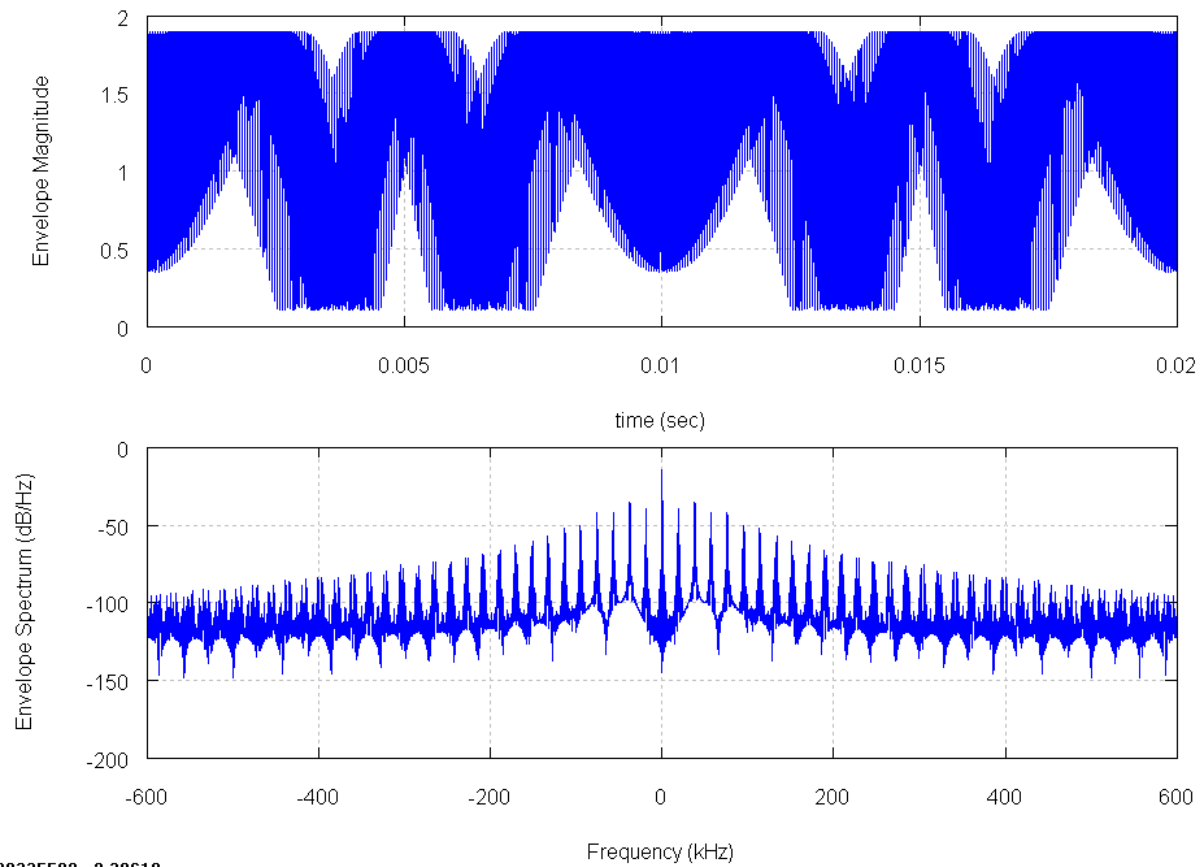Peak Frequency Deviation = 75 kHz

Figure 1

0.000603420, -0.792508

Figure 6 Stereo Case (single tone, Fm = 1000 Hz)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
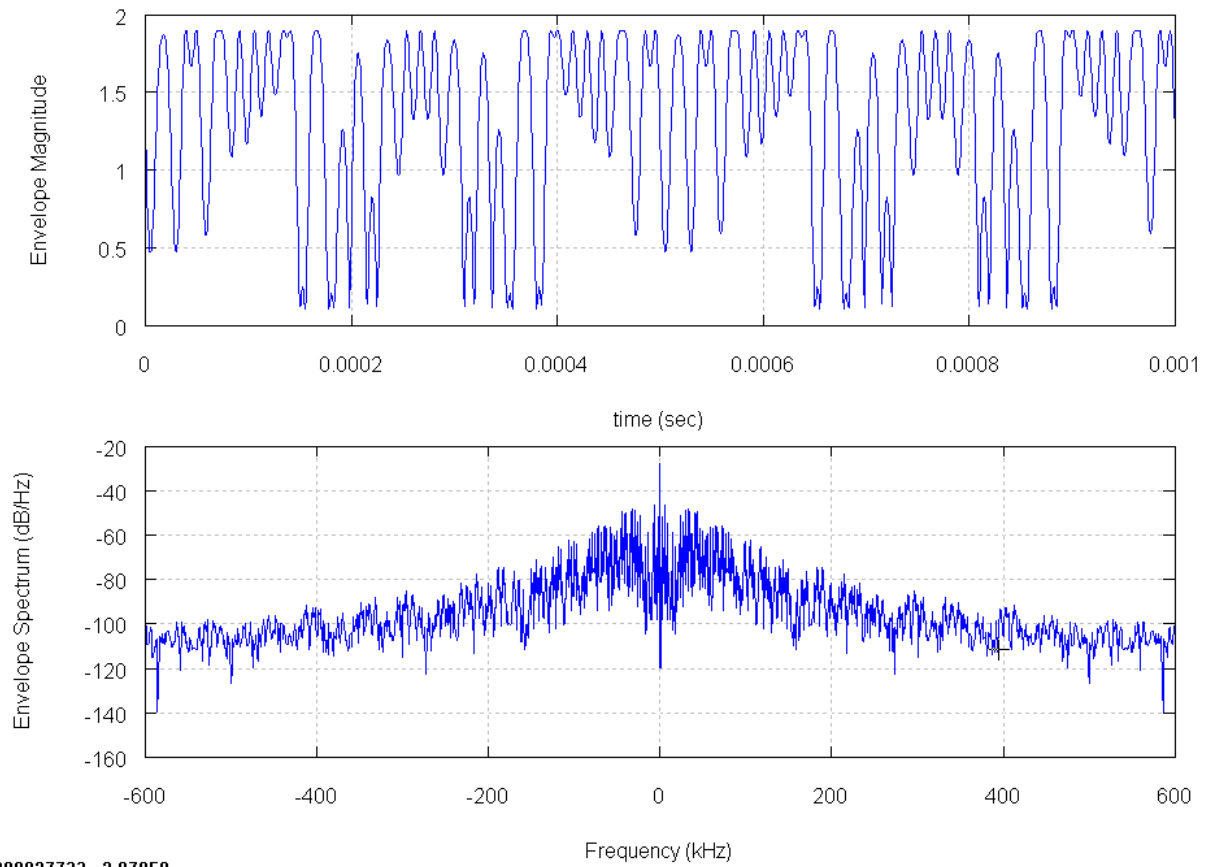Peak Frequency Deviation = 75 kHz

1.16780e-005, 1.35407

Figure 7 DSB Stereo Case (single tone, Fm = 15000 Hz)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
Peak Frequency Deviation = 75 kHz

Figure 1

-0.00335502, 2.30619

Figure 8 SSB Stereo Case (single tone, Fm = 50 Hz, LSB)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
Peak Frequency Deviation = 75 kHz

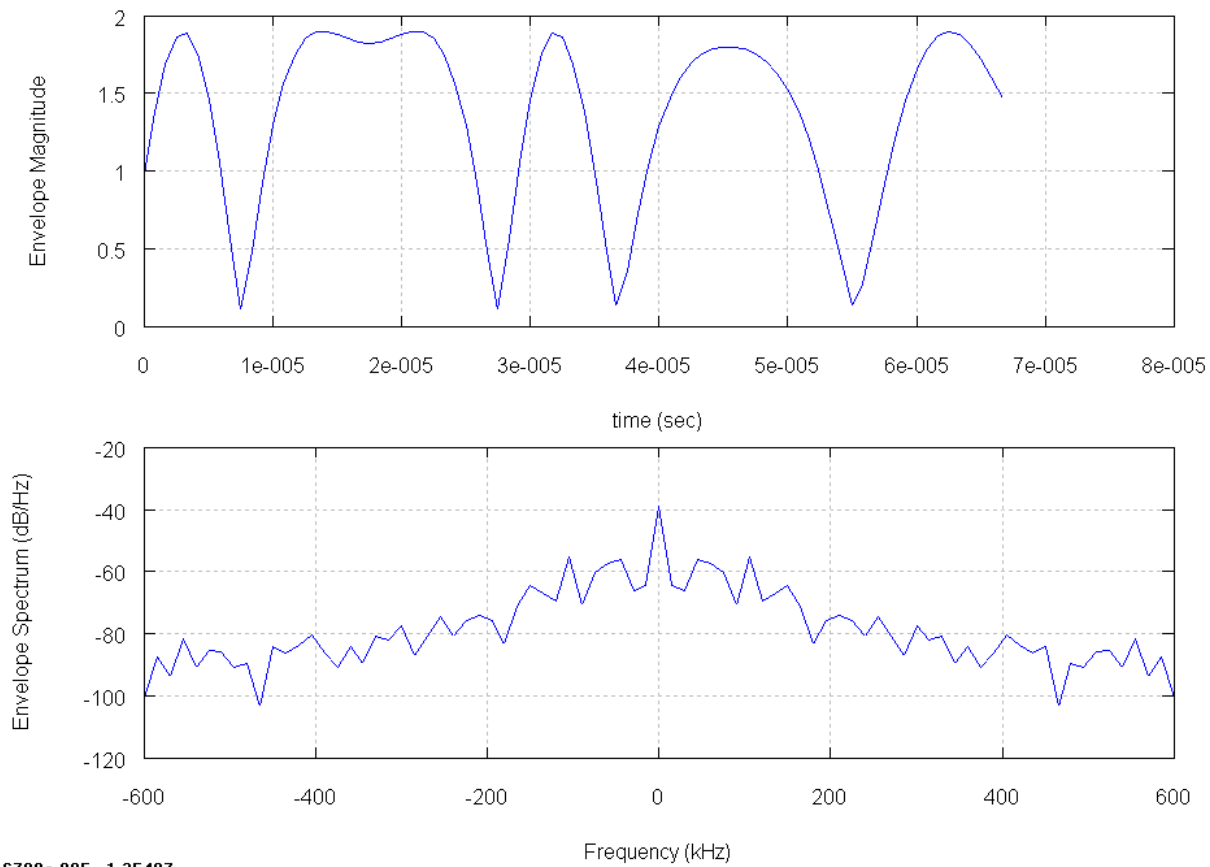**Figure 9** SSB Stereo Case (single tone, Fm = 1000 Hz, LSB)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
Peak Frequency Deviation = 75 kHz

Figure 10 SSB Stereo Case (single tone, Fm = 15000 Hz, LSB)
Single Reflection Delay = 35 us, 90% of Main Signal Amplitude
Peak Frequency Deviation = 75 kHz

Comparing the envelope diagrams of the DSB and SSB stereo cases can be tedious but it is clear that the more complicated audio waveforms of both types of stereo modulation cause much distortion of the FM envelope under severe multipath conditions. To make the comparison a bit easier to see quantitatively, the AM spectra of each envelope were plotted and can be used to form a more direct comparison of the results. For example, compare the AM spectra of Figures 5 and 8 which depict DSB and SSB stereo left only at 50 Hz respectively. It is clear that under identical time delay and amplitude conditions of the two FM signals that the AM noise component is greater for that of the SSB case shown in Figure 8 than the normal DSB case shown in Figure 5. In the DSB case the AM side bands are down to 100 dB below reference from 400 kHz to 600 kHz away from carrier center. In the SSB case the AM side bands fall to just under 100 dB starting at 600 kHz away from carrier center. It is clear that more AM distortion is being created for the SSB case than the DSB case under otherwise identical conditions. The DSB and SSB 1 kHz modulation cases depicted in Figures 6 and 9 respectively show the same trend where at 200 kHz away from the carrier the AM side band energy is 90 dB below the carrier and the SSB case shown in Figure 9 shows AM side band energy approximately 10 dB worse. A comparison of the DSB and SSB 15 kHz cases depicted in Figures 7 and 10 respectively show that the result is slightly better for the SSB case.

To do a further comparison that puts a single figure of merit for each case a calculation using Parseval's theorem was performed that allows each case to be assigned a degradation of FM signal number in dB. Out of curiosity a run for USB was also performed to show it for comparison sake. Interestingly, this comparison shows that for tone modulation that monaural broadcasting suffers from the worst degradation. The comparison between DSB and LSB appears to be very much the same except for the 15 kHz case where the LSB case is 0.69 dB better. The comparison shows that one stereo case is not demonstrably better than the other.

It is likely that with the LSB case at 15 kHz modulation which actually shows some improvement is due to the fact that most of the modulation spectral density is closer to the carrier. On average it appears that for the sake of synchronous AM modulation of the FM carrier there is intrinsic benefit to use any other type of linear modulation than that of DSB which is presently in use.

Degradation of FM signal due to multipath with respect to a multipath-free environment (in dB)*

Tone (Hz)	Monaural	Stereo (DSB)	Stereo (LSB)	Stereo (USB)
50	3.94	2.52	2.54	2.55
1000	3.94	2.51	2.50	2.57
15000	4.20	4.21	3.52	4.23

*Multipath is single-reflection, 90% of main signal amplitude and 35 us delay.
Tabulated values are based on:*

$$Degradation \ \ dB = 10\log_{10} \frac{\sum_t E \ t_{\ normalized}{}^2}{\sum_t E \ t_{\ ,no \ multipath}{}^2}$$

In 1987 I was interested in seeing if this same technology showed promise as the author of the SSB proposal did. At that time Broadcast Devices, Inc. designed and built a first and second generation SSB stereo generator system whereby the lower side band of the stereo sub carrier was transmitted. The phasing method utilizing a high quality Hilbert transformer was employed. Two difficulties were noted almost immediately. First, the SSB modulator modulation control of the FM carrier was difficult to control when fed with processed audio. This owes to the fact that the Hilbert transform is an asymptotic function and causes the carrier of the SSB modulator to peak in proportion to the derivative of the modulating function. Modern audio processors re-shape the audio waveform to maximize loudness of the FM signal in such a way as to produce highly transient and therefore high derivative content audio. Therefore the peak to average ratio of the SSB modulator and the peak deviation of the FM transmitter are difficult to control. Special processing of the audio is necessary to make this system workable at best. This problem has long been understood in the communications field. A method to mitigate this effect is to utilize vestigial side band transmission such as was used with analog television whereby the low frequency components of the unwanted side band are allowed to modulate the transmitter with the full desired side band. Even with VSB modulation the peak to average ratio of the stereo sub carrier will be higher than that of the DSB sub carrier presently being used.

The second problem that occurred in actual field tests of the BDI SSB system was discovered when this system was tested on several FM stations in the New York metropolitan area. Comparison A/B testing of the normal DSB stereo generator and the SSB generator were performed and it was clearly evident that the SSB modulator generated much more receiver distortion as compared to the DSB case. At the time, a moving vehicle evaluated reception while the stereo generators were alternately switched between over identical paths. Most notably the West Side Highway in New York City from the George Washington Bridge to mid town at 57th Street which is a long known multipath prone area showed higher degradation of signal reception with SSB

transmission. The station used for these tests broadcasted from the Empire State Building. The system was tested on two other stations in the area, one serves the lower Hudson Valley of New York State and the other was a local FM class A station serving Westchester County in New York. The reception reports for all three stations were similar in that the SSB case was determined to be no better and in some cases worse than the DSB case. The mathematical simulations in this paper concur with the anecdotal result of our earlier work. Work on this system was abandoned after it was determined that the system produced no net benefit. The mathematical model and actual field tests seem to indicate that at best there is no improvement using SSB technology and in fact under dynamic conditions which were encountered by the field tests it performed slightly worse than the DSB system. The reason for this is believed to be the fact that today as then modern audio processing equipment used by FM broadcasters tend to compress the low frequency content of the audio spectrum in such a way that the average injection level of the stereo sub carrier is made to be statistically higher near the sub carrier frequency. With the DSB case the injection level is never more than -12 dB higher than maximum peak deviation. With the SSB case there is a doubling of the average injection level of the sub carrier at -6dB below maximum peak deviation. It is believed that the highly concentrated low frequency content injected at double the normal average causes the increased AM noise noted in our reception tests. As can be seen from the AM noise plots that in fact the higher the modulation index the higher the potential for synchronous AM noise in a high multipath environment. It is suggested that at a minimum that testing of any such SSB system under dynamic modulation conditions be performed in the laboratory using a suitable multipath simulator in addition to on air tests to determine suitability.

Conclusion

The recent proposal to revive this technology prompted me to examine this using a mathematical model to determine the actual cause of our results from more than two decades ago. The model in this paper is an attempt to verify the anecdotal field testing data from long ago. I believe that this paper illustrates the problems of FM reception and shows a mathematical treatment of a very longstanding problem with FM propagation in difficult terrain areas. It is my conclusion that the proposed SSB stereo system seems to indicate that there is not a significant benefit to reception. In fact in some cases may actually provide worse reception characteristics due to dynamic modulation conditions. In reviewing the notes that were taken on this long ago and the plots shown in this paper it is clear that a more thorough review of this matter should be undertaken before any thought of adoption by the broadcast industry be contemplated. Clearly, more study of this matter should be undertaken as the mathematical model shown in this paper depicts simple cases with a limited number of interfering signals and simple tone modulation where modern audio processing techniques were not taken into account. Dynamic testing should be included in any study of efficacy of this technology.

Bibliography

Information, Transmission Modulation and Noise – Schwartz, Mischa. 1971

Frequency Modulation Distortion Caused by Multipath Transmission – Corrington, Murlan. S. IRE Proceedings Dec.1945

Single Side Band FM Stereo Transmission – Tarsio, Robert C.; Burgert, Frank P. Viacom Broadcast Group NAB Presentation April 1987

Single Side Band Systems & Circuits – Sabin, William E.; Schoennike Edgar O. 1964