INTRODUCTION TO THE

MOTOROLA C-QUAM AM STEREO SYSTEM

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Introduction to the Motorola C–Quam AM Stereo System

INTRODUCTION

There are five basic techniques for adding stereo to standard AM broadcast transmissions. These five were proposed to the FCC in the AM stereo proceeding and four of the five continue to vie for acceptance by the broadcasters and receiver manufacturers. The Motorola C-Quam system has always been the best system from practically any viewpoint, but it has been more difficult to communicate the superiority because C-Quam appears to be more complex than the others. It is hoped that the following information is presented to provide a clear explanation of the advantages of C-Quam and the reasons why the other systems are less acceptable.

SYSTEM SIMILARITIES

There are many similarities among the five systems and that is why some have thought that they must all perform about the same way. For instance, all systems (except Harris[1]) combine left channel and right audio into left plus right (L + R) and transmit it as amplitude modulation. This of course must be done in order to continue to provide standard AM for the existing AM receivers and any future listening on ordinary monaural receiving equipment. Also, all systems combine the left and right audio in a subtraction process (L – R) to modulate the transmitter in some form of frequency, phase, or quadrature modulation. This angular modulation is not readily demodulated by ordinary AM radios to a significant degree to bother the reception to monaural equipment. Although all systems use this angular modulation to transmit the stereo information, it is the precise methods of generating and detecting this additional stereo information that determine the differences in system performance. Characteristics such as spectrum occupancy, stereo coverage, noise performance, fidelity, separation, susceptiblity to interference and performance under heavy amplitude modulation are important to the broadcaster, receiver manufacturer and listener.

THE SYSTEM DIFFERENCES

The systems can be categorized in a number of ways. Below is one technique organizing the systems according to basic emission families.

MIXED MODE	PHASING SSB	QUADRATURE
Belar (RCA AM/FM)	Kahn	Motorola C-Quam
Magnavox (AM/FM)		Harris No. 1
		Harris No. 2
		Harris No. 3

MIXED MODE

Mixed mode means amplitude modulation is used for the main (L + R) signal, and a completely different and independent type of emission, frequency or phase modulation is used for the stereo (L – R) information. The Belar AM/FM system was invented by RCA and tested in the late fifties on WRCA (WNBC) and subsequently not pursued further.

The Magnavox system uses amplitude modulation for the main (L + R) channel and pure phase modulation for the stereo (L – R) information. Murray Crosby experimented with phase modulation of high frequency signals in the thirties and found that it also was impractical because it consistently gave higher distortion than AM especially on skywave transmissions. The AM/FM stereo system is particularly susceptible to distortion due to mistuning, I.F. assymetry, antenna bandwidth limitations, directional antenna nulls and various propagation anomalies. Phase modulation is good for transmission systems such as VHF telemetry links, but it is not good for medium and high frequency transmission of high quality audio.

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[1] The Harris systems transmit imperfect AM at maximum distortion levels of approximately 4 percent.

"COMPATIBLE" SIGNAL SIDEBAND

Phasing single sideband was developed in the thirties and was used by AT&T for communications circuits for multiplexing of voice and teletype over H. F. links. For AM stereo the problem is distortion when trying to make the system compatible with ordinary monophonic receivers. It is possible to generate and recover one set of sidebands with very good fidelity because the carrier frequency component of the transmission can be made to perfectly complement the required sidebands. However it is not possible to transmit and receive two independent signals on two separate sets of sidebands perfectly because the carrier component cannot satisfy the needs of both sets of sidebands at the same time. Of course it can be imperfectly done with distortion. In addition, it is also impossible to generate two independent sidebands and a carrier, and detect the resultant on an envelope detector as the sum of the two channels without distortion. So called "compatible" single sideband or independent sideband attempts to do it all but unfortunately it just cannot be done. The result is a rather shoddy compromise in distortion which under certain stereo conditions create more than 25% intermodulation distortion between left and right channels, and it can never be fixed . . . its built into the system.

QUADRATURE SYSTEMS

AM quadrature modulation will be explained more fully later, but basically look at it as two AM transmitters, phase locked together, the outputs coupled together, but the carriers set to a phase difference of 90 degrees. The audio from each transmitter can be separated at the receiving end by using phase sensitive AM detectors.

The problem with quadrature modulation is that it produces distortion in normal AM envelope detectors, so with AM stereo it isn't immediately compatible with the millions of existing radios.

Philco developed an experimental AM stereo system in the late fifties using quadrature modulation and tested it on WABC in New York. Also, CBS, in the early sixties, tried out a very similar system and conducted experimental transmissions on WCBS also in New York. Philco did propose the system to the FCC in the AM-FM and TV stereo proceedings in the late fifties, but the Commission rejected all AM stereo systems at that time. CBS did not pursue its system further.

Harris has tried **three** times to make a quadrature AM stereo system that is compatible with existing radios and still hasn't found what could be considered a satisfactory answer.

HARRIS TRY NO. 1:

The first attempt was to not use a 90 degree phase difference but to use a reduced angle ($\pm$ 15^{o}). The reason is, the closer together the two transmitters are to no phase difference, the closer the transmitted signal is to AM . . . OK for compatibility, but the amount of stereo information is drastically reduced, thereby limiting stereo coverage to far less that monaural coverage.

HARRIS TRY NO. 2:

To try and combat the stereo coverage problem, Harris modified its system to use a synchronized compression/expression (companding) scheme. By compressing the transmitted stereo audio and expanding it at the receiver, the stereo signal to noise ratio supposedly would be improved. In order to control the expansion process in the receiver, a variable frequency pilot tone was transmitted in the L – R channel from 55 to 96 Hz. The frequency was proportional to the required gain control of the receiver expander. This meant that all L – R stereo audio had to be filtered out of that range to make way for the pilot, therefore creating no stereo for audio frequencies under approximately 200 to 300 Hz. In addition, under heavy stereo content the system coverage reverts to system try No. 1.

Of course companding can be used in any communications system, including any of the other AM stereo systems, but what killed the Harris No. 2 try was that no receiver manufacturer would build a radio using such a complicated and difficult system. It simply is too unreliable and/or expensive to dig out of the transmitted signal a pilot tone jumping around in frequency and derive a control function from it. Besides, the resulting performance left a lot to be desired.

HARRIS TRY NO. 3:

The latest Harris system abandons the variable pilot tone frequency and sets the pilot to 55 Hz. Although the details are not fully known, it is believed that the L – R modulation is controlled by a special audio processing device which limits the maximum angle of quadrature modulation in an attempt to prevent excessive AM incompatibility. However, in doing this proper separation can only occur up to a certain threshold of light stereo modulation.

Beyond that threshold under heavy left or right only modulation separation degrades down to as low as only 8 dB. Thus, in Harris try no. 3, Harris has a) reduced the quadrature angle, b) given up separation at low frequencies, c) had to use special audio processing techniques, and d) given up separation at high modulation levels. And still the stereo distortion caused to an AM radio (or a station modulation monitor) can exceed 4% and that is not equipment limitations, that's built into the system, period! Transmitter and receiver distortions can add to this fundamental system distortion of over 4%.

Quadrature modulation is a good idea, but CBS tried, Philco tried, and Harris tried three times, and none found a satisfactory way to make it work while maintaining compatibility with existing envelope detectors in AM radios.

THE MOTOROLA COMPATIBLE QUADRATURE SYSTEM

While Philco, CBS and Harris have all been unsuccessful in implementing a quadrature system, Motorola found a way to take advantage of the quadrature characteristics while maintaining monaural compatibility. The Motorola system extracts the phase modulation component of a full quadrature signal and transmits that as the L – R stereo information. The L + R signal is transmitted as the normal AM signal providing excellent compatibility with AM receivers. The resultant signal under normal stereo modulation providing the advantages of full quadrature.

BACKGROUND OF THE MOTOROLA SYSTEM

For many years, scientists and engineers have attempted to find ways of transmitting and receiving more and more information while using less and less bandwidth. The AM stereo systems are a good example of just that, multiplexing another channel along with an existing one in order to transmit more information.

Communication systems can be mathematically modeled, including factors such as transmitted signal, channel bandwidth, signal to noise levels, distortion, crosstalk and other parameters. Motorola has devoted a considerable effort in its research and development in many areas of communication theory and has a corporate research section called the modulation laboratory. There, an ongoing program seeks out ways of improving transmission efficiency, and the results of this research can be applied to many communication systems, including broadcasting.

Motorola made major fundamental contributions to the development of the NTSC system of color television transmission which used quadrature modulation for transmission of the color information mixed in with the monochrome picture information. The Motorola C-Quam AM stereo system was originally conceived as a mathematical model of a high technology communication system by the corporate research and development staff, and was proven mathematically to be superior before anyone touched a soldering iron. The Motorola AM stereo system has not changed in concept since it was first invented mathematically and has proven in operation to be exactly as predicted by the math.

WHAT'S SO GREAT ABOUT QUADRATURE?

As was briefly described earlier, quadrature combines two signals at a phase angle of 90 degrees for transmission, and then at the receiver separates them again. It is another form of multiplexing. This technique is used to transmit the color information in the U.S. TV color system and is used for encoding of SQ and QS quadraphonic records. In the application to AM stereo, quadrature is really transmitting two AM signals on the same channel. For relatively narrow bandwidth applications such as we have with AM radio, AM is really the most efficient emission because amplitude modulation requires the minimum bandwidth and it is independent of noise. What that means is that in an AM receiver, the effective background noise remains the same with or without modulation. This is not so with FM or PM, which under modulation, "kicks up" additional noise not present under no modulation conditions. So in AM quadrature, an additional channel can be created and heavily modulated without "kicking up" excessive noise. In other words, for narrow bandwidth communications systems, there is a signal to noise advantage to using AM quadrature.

Another important point is for AM stereo the long transmission path from the transmitter, through a directional antenna, over a difficult propagation path, and through a narrow bandwidth and possibly mistuned receiver is a very rough one. In order to be demodulated with the least distortion and maintaining separation, the signal must be very resilient . . . able to withstand the difficult transmission experience. This also is best done with AM quadrature because two of the same type of signals are being transmitted and therefore undergo the same type of distortions which can in many instances be canceled at the other end. In other words, for AM stereo the differences between the two signals must be preserved, and if each undergoes the identical distortions during transmission, the differences between the two signals will be maintained. This is another reason why the AM/FM and AM/FM stereo systems are not very good because distortions to the AM component are very different from the distortions to the PM or FM component during transmission, and the result is a much more distorted AM stereo signal.

Although many have tried to use AM quadrature for AM stereo the most difficulty is encountered when modifications are made to make it compatible with envelope detectors in existing AM radios. The Motorola scientists and engineers found a way of taking advantage of the quadrature characteristics, while transmitting a perfectly compatible AM component.

THE NATURE OF AM AND FM SIDEBANDS

In order to describe the system, some basics must be understood about certain types of modulation and how it is detected or not detected. To check our understanding, let's look at two basic types of transmission, AM and FM, modulated by a very low distortion sine wave.

When a signal is amplitude modulated by a sine wave, we can describe it in several ways. One is to simply look at the amplitude and trace it vs. time. This would be the typical display on an oscilloscope of the R.F. envelope. See Figure 1. Another is to look at it on a spectrum analyzer which would show three vertical lines in the center, a taller line representing the carrier, and the two sidebands, lesser in amplitude, shown on either side of the carrier. In these two representations, there is no phase information given but for now think of the two sidebands as being in-phase sidebands or "I" sidebands. Thus in a perfect AM signal with no distortion there are no higher order sidebands or harmonics of the primary AM sidebands and there is no net phase modulation of the total of the carrier and the two sidebands.

The other case, FM (or PM) is where the phase or frequency is modulated according to our low distortion sine wave, and let's say the deviation is at least a few kHz. In this case, the R.F. envelope does not vary and the A.C. output of the envelope detector would be zero. The spectrum, however, would usually consist of a component at the carrier frequency and a family of sidebands located a multiples of the modulating frequency away from the carrier. For instance if the carrier frequency was 1000 kHz, and the modulation was 1 kHz, there would be symmetrical sidebands at 999 and 1001 kHz, 998 and 1002 kHz, and so on.

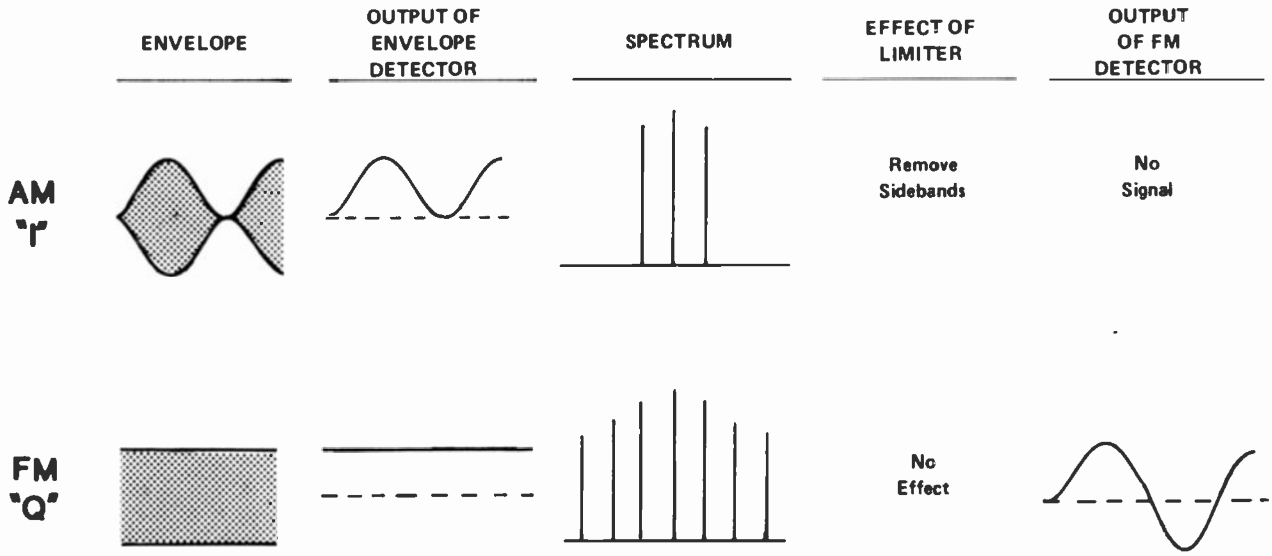


Figure 1.

If there is a carrier and sidebands, why doesn't the envelope detector detect the modulation? The reason is that in FM and PM, the instaneous phase and amplitude of the carrier component and all the sidebands always add up to the same power as the unmodulated carrier. As the modulation is turned up, the carrier is reduced in amplitude and the missing carrier power is given to the sidebands, but the sum total at all times remains the same. It is in the phasing of the sidebands that determines whether they will add and subtract with the carrier to produce differences in amplitude or whether they will add and subtract with the carrier component to always give the same amplitude. In the case of FM or PM, let's call the sidebands quadrature or "Q" sidebands.

Now, the interesting thing is that "Q" sidebands don't need a linear amplifier to be amplified and can be crunched to death by limiters and class C amplifiers and still the same spectrum comes out the other end. On the other hand "I" sidebands must have linear amplification in order to survive and can be totally stripped from the signal by a good limiter. An envelope detector will be blind to the existence of perfect PM or FM sidebands, and a phase or frequency demodulator will not see perfect "I" sidebands or amplitude modulation.

Another interesting fact is that all modulation can be represented by a combination of the "I" sideband components and the "Q" sideband components. This is very important in AM stereo broadcasting because it is necessary to split any of the AM stereo system's signals into the "I" and "Q" signals for transmission on an existing AM transmitter. See Figure 2. For all systems, the "I" signal is given to the transmitter in audio form at the audio input to the transmitter and then it amplitude modulates the signal in the normal way recreating an AM or an "I" sideband signal. For all systems, the "Q" components are fed to the transmitter in R.F. form as a phase modulated signal that replaces the crystal oscillator in the transmitter. Of course the "Q" signal sidebands can pass through the intermediate and final amplifier R.F. stages of the transmitter even though these stages are non linear and usually operate class C. The Motorola AM stereo system also required that it be reconstructed for such transmission but certain modifications are made for compatibility with the millions of existing AM radios.

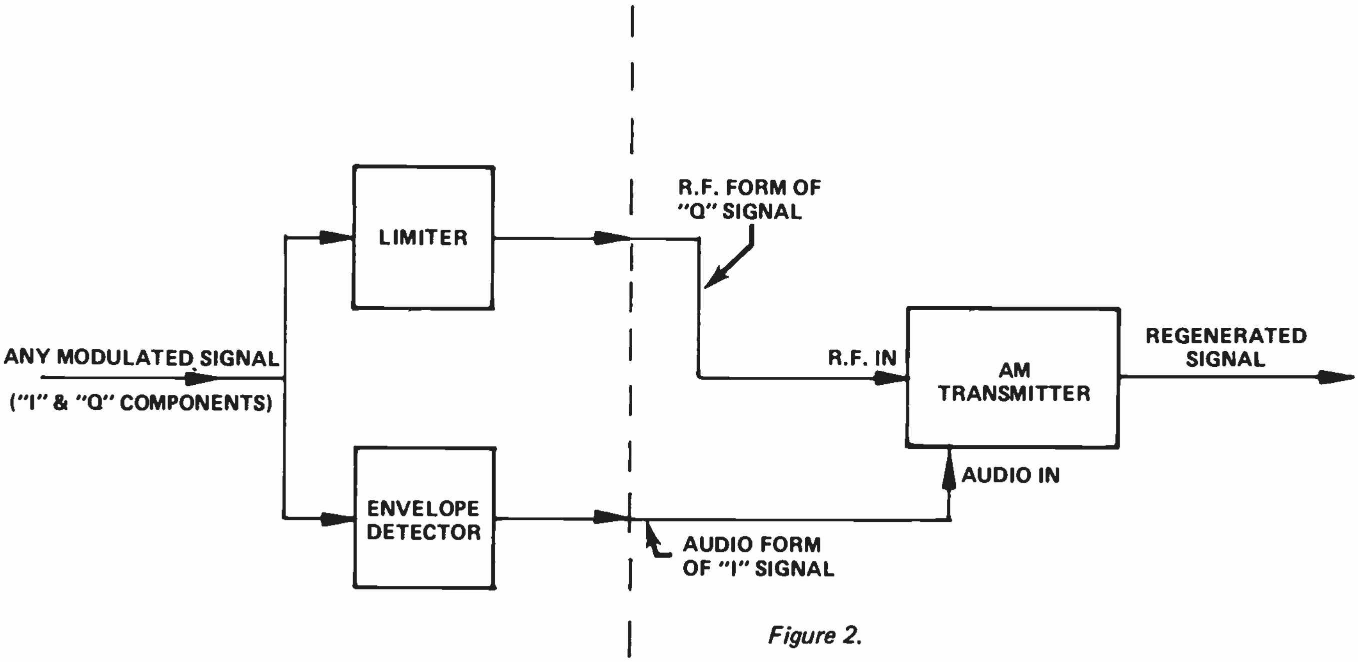


Figure 2.

PURE QUADRATURE

Observe Figure 3. Pure AM-AM quadrature can be generated by two transmitters connected so that their outputs add. One transmitter would be a standard AM generator producing the carrier at, let's say, zero phase, and sidebands associated with that carrier ("I" sidebands). A second transmitter is fed from the same master oscillator as the AM transmitter, but the phase is shifted 90 degrees. Because we already have a full carrier at zero degrees phase from the AM transmitter providing a phase reference for the receiver, the second transmitter does not need a carrier and is set up with a balanced modulator cancelling out the carrier and producing only sidebands. Because these sidebands are generated from a carrier which is 90 degrees out of phase from the AM transmitter, these sidebands will be 90 degrees out of phase with the AM sidebands and "in quadrature." These become our "Q" sidebands.

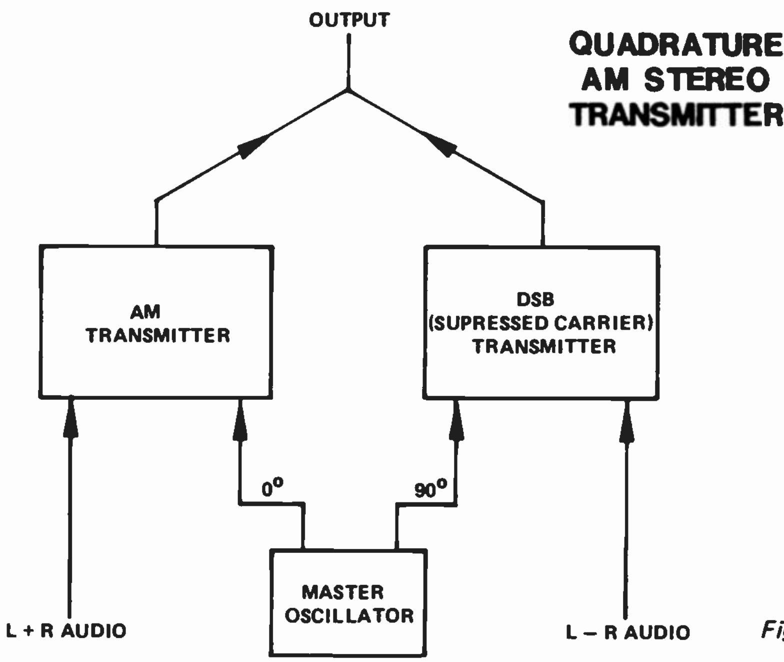


Figure 3.

If we wanted to make an AM stereo system we could transmit L + R into the AM transmitter, and L — R into the double sideband transmitter. Sounds good, but under left or right only conditions where both transmitters are contributing sidebands to the output, the resultant would be a distorted AM signal. Before we look at why, let's take a look at a quadrature demodulator which is also the widely touted synchronous detector.

THE QUADRATURE (SYNCHRONOUS) DETECTOR

To recover the audio signals separately at the receiver a system of phase sensitive detectors is arranged. See Figure 4. First, a reference phase must be derived from the transmitted signal. This is the carrier by means of a phase locked loop (PLL).

The device that is primarily responsible for the operation of the synchronous detector is the balanced demodulator or product detector. When this device is given an input signal and a reference carrier, it will provide at its output the difference of the two signals. If the two signals are identical in frequency and 90 degrees out of phase, the output will be zero. If there is a constant difference in phase it will give a D.C. output or if the phase is varying it will give an A.C. output. The D.C. output of the "Q" detector is fed back to a voltage controlled oscillator (VCO) which causes the frequency and phase of that oscillator to zero in on the input carrier frequency and phase and lock to it.

This provides the phase reference for the "I" and "Q" detectors. The A.C. output from the "I" demodulator provides the original L + R audio from the AM transmitter, but it does not see the "Q" sidebands from the double sideband transmitter. The second demodulator is also fed from the VCO but its carrier reference signal is automatically shifted 90 degrees. Therefore it sees the "Q" sidebands from the double sideband transmitter and sees nothing from the AM transmitter input audio which is L + R.

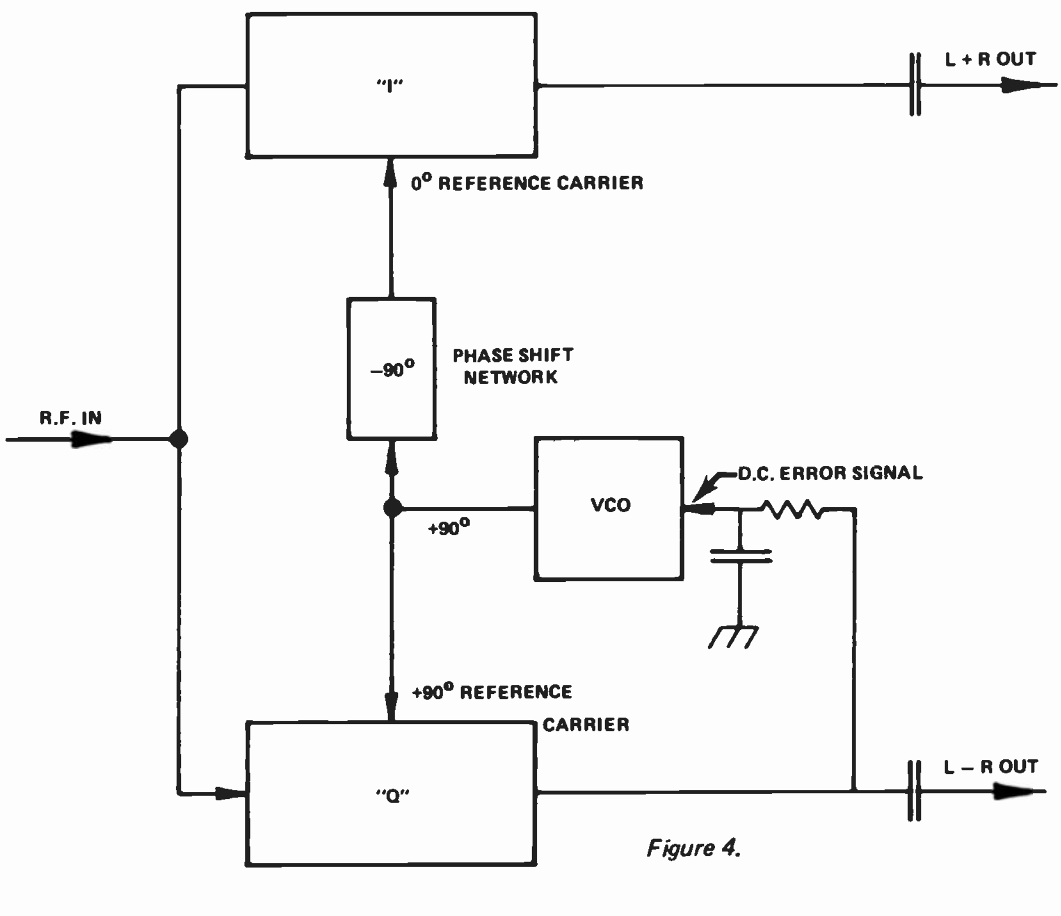


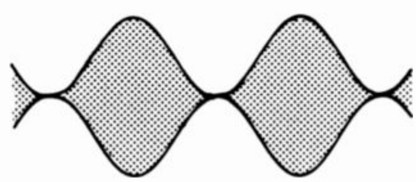
Figure 4.

The AM-AM quadrature system would be excellent for AM stereo except that the envelope detectors in normal AM radios don't see only the "I" sidebands or the "Q" sidebands but see the simple vector addition of both. The envelope detector is not capable of seeing any phase information and only sees the absolute total of the modulation regardless of phase.

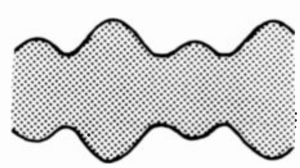
Under L + R (L = R) only modulation conditions (monaural), there is no problem, because only the AM transmitter is modulated and the envelope detector recovers AM perfectly. (The double sideband transmitter receives no audio because when L = R, L – R = 0.) However, under stereo conditions, for instance, when L only is transmitted, full sideband components are contributed by both the AM and double sideband transmitters and the envelope looks like Figure 5. This would not be compatible with existing radios and a very distorted signal would be heard.

So, there's the problem . . . compatibility, and neither CBS, Philco or Harris has found a satisfactory answer. Now comes Motorola.

QUADRATURE MODULATION ENVELOPES



L + R MODULATION



L ONLY OR R ONLY

Figure 5.

COMPATIBLE QUADRATURE

The Motorola AM stereo system is not complicated at all. It simply takes a pure quadrature signal as just described, and extracts the phase modulation components of the quadrature signal and phase modulates the broadcast transmitter, and sends L + R audio to the audio input of the transmitter. That's it! The advantage is that a very nice AM signal is always transmitted so that the envelope detectors are happy, but that the phase modulation of the carrier is derived from quadrature. The result is a signal with the advantages of quadrature modulation while maintaining monaural compatability.

THE C-QUAM TRANSMITTER

The C-Quam transmitter is diagramed in Figure 6. Note that pure quadrature is generated by taking L + R and L — R and modulating two balanced modulators fed with R.F. signals out of phase by 90 degrees. In this case the 90 degrees phase shift is derived by using a Johnson counter which divides an input frequency (four times station carrier frequency) by four and automatically provides digital signals precisely 90 degrees out of phase for the balanced modulators. The carrier is inserted directly from the Johnson counter. At the output of the summing network, the result is a pure quadrature AM stereo signal. From there it is passed through a limiter which strips the AM components from the signal and leaves only the phase modulation "Q" sidebands. This is not the same as the simple output of the "Q" modulator because the addition of the "I" and "Q" balanced modulators produced some phase shifting not present in the "Q" modulator alone. The output of the limiter is amplified and sent to the broadcast transmitter in place of the crystal oscillator.

The left and right audio signals are precisely added and sent to the audio input terminals of the broadcast transmitter. That's the Motorola C-Quam encoder.

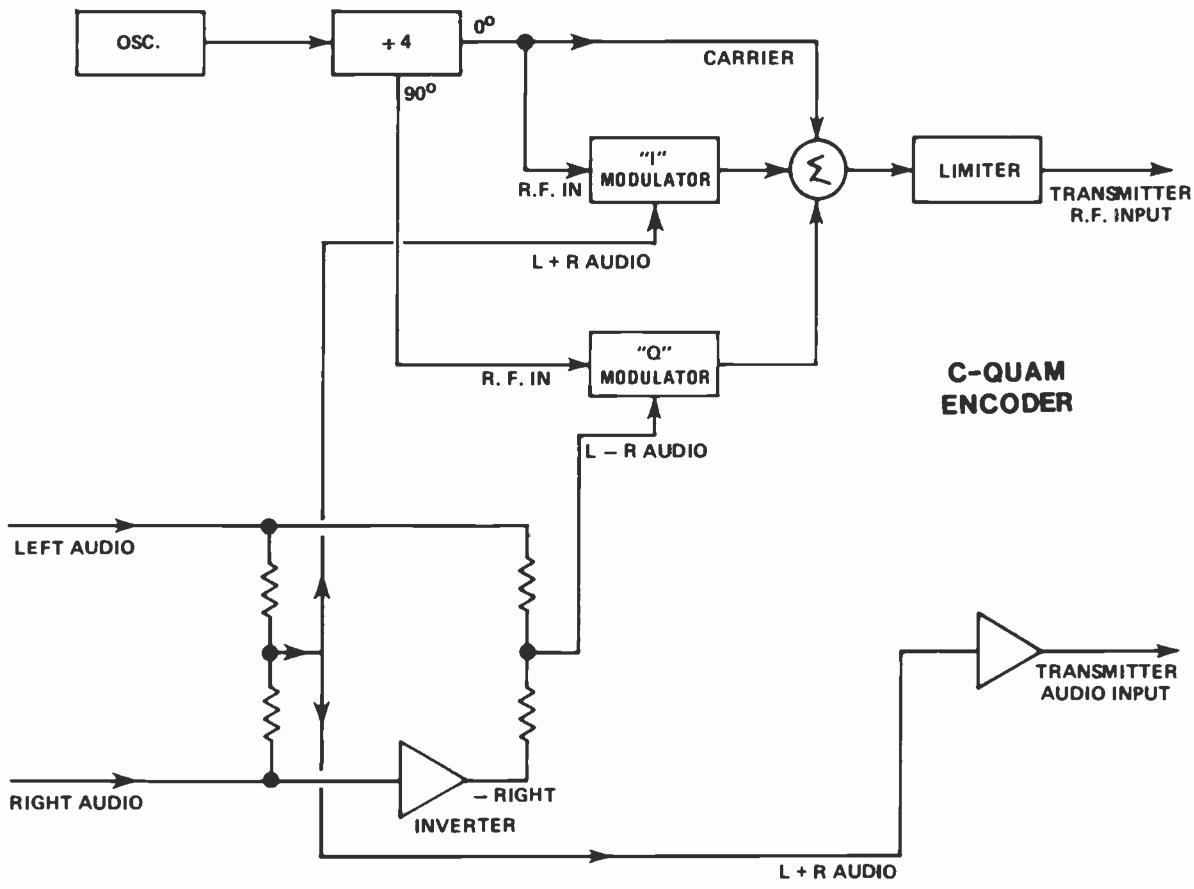


Figure 6.

DECODING C-QUAM

C-Quam is decoded by simply converting the broadcast signal which is already "almost" pure quadrature to pure quadrature and then using a quadrature detector to extract and L — R. Refer to Figure 7. Note that the demodulator contains a section which is the pure quadrature demodulator as previously described. In order to prepare the broadcast signal for the quadrature demodulator, it has to be converted from the envelope detector compatible signal that is broadcast to the original quadrature signal that was not envelope detector compatible. This is done by demodulating the broadcast signal two ways; with an envelope detector, and with an "I" detector. The two signals are compared and the resultant error signal is used to gain modulate the input of the "I" and "Q" demodulators.

When the transmitted signal is L + R (monaural, no stereo) the transmitted signal is pure AM or only "I" sidebands. In this case the envelope detector and the "I" demodulator see the same thing. There is no error signal, the input modulator does nothing and the signal passes through without change. However, when a left or right only signal is transmitted, both AM and PM is transmitted and the input signal is shifted in phase to the "I" demodulator and loses some of its "I" amplitude. The envelope detector sees no difference in the AM because of the phase modulation, and when the envelope detector and the "I" demodulator are compared, there is an error signal. The error signal pushes up the input level to the detector. This makes the input signal to the "I" and "Q" demodulators look like a pure quadrature signal and the audio output gives a perfect and L – R signal. The demodulator output is combined with the envelope detector output in a matrix to give left and right audio out.

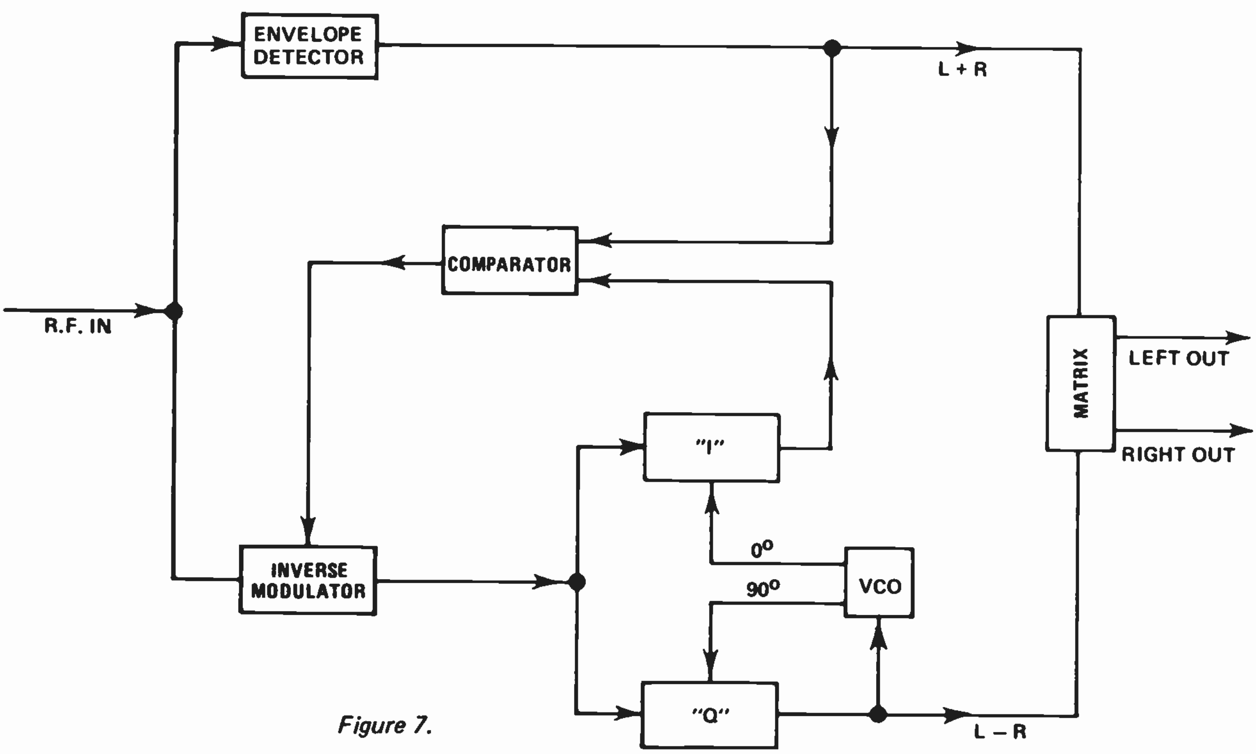


Figure 7.

SYSTEM PERFORMANCE UNDER HEAVY MODULATION

There are many advantages of the Motorola system. One is its performance under 100 percent negative amplitude modulation conditions. When the carrier momentarily goes to zero as in 100 percent negative modulation, the output of the envelope detector becomes zero. Because of the action of the comparator and inverse modulator, the output of the I demodulator goes to zero. Simultaneously, the output of the Q demodulator also is forced to go to zero. This means that there will be no noise popping from the stereo channel under 100 percent negative amplitude modulation as is experienced, for instance, in the mixed mode systems.

THEORETICAL AUDIO PERFORMANCE

There is no theoretical limit to the audio frequency response, to the lower limit of distortion or the separation of the Motorola system. All of these characteristics are primarily limited by the performance of the encoder, AM transmitter, and modulation monitor or receiver. The only other limit would be due to the bandwidth of emissions under stereo modulation conditions with single tone modulations above 7500 Hz. It is possible to force the system to exceed the FCC bandwidth limits permitted for AM stations by a few dB. However, under the most heavily processed and pre-emphasized stereo program conditions, the emissions are much below FCC requirements for bandwidth.

ACTUAL STEREO PERFORMANCE

The actual measured performance of the Motorola system connected to a typical plate modulated AM broadcast transmitter is excellent, nearly that of FM stereo. The frequency response of left or right only transmissions is basically the same as the AM response of the transmitter, in the case of tests made at WIRE in Indianapolis, about 1 dB down from 30 Hz to 12 kHz. The separation was held to better than 30 dB from 100 Hz to 7.5 kHz and within 20 dB from 50 to 10 kHz. Distortion of the left or right only transmissions were below 1.5 percent from about 80 Hz to 7.5 kHz. This data is taken from actual measurements made from an AM stereo modulation monitor.

RECEIVER AUDIO AND COVERAGE

Because the Motorola AM stereo system acts like a full quadrature system under normal stereo conditions, its signal to noise characteristics are excellent. Under typical stereo programming, the increase in noise is estimated to be about 1.5 dB which is nearly imperceptible. In other words, the stereo coverage of the Motorola system is essentially the same as the monaural AM coverage.

The audio fidelity that can be expected from AM stereo radios depends upon the receiver design. It is possible to produce an AM stereo radio which will be comparable to FM in fidelity but because the AM stations are spaced at 10 kHz intervals, too much interference from other stations would probably be heard. In the past, receiver manufacturers were generally not willing to make AM radios with better fidelity because they felt that there was no demand for such equipment. With AM stereo, the ability to offer "stereo" means a much more attractive product which will allow a high price. Therefore the AM stereo radio designer will have a much wider lattitude in designing the receiver selectively and will be more able to get a higher fidelity while holding down the suseptibility to adjacent channel interference. With more expensive I.F. selectivity, the receiver designer can obtain an audio response out to nearly 5 kHz while still rejecting the adjacent channel interference.

While this audio response may not sound comparable to FM stereo, 5 kHz audio is actually very similar to the typical acoustical response found in many FM automobile radios. FM stereo has severe multipath and picket fence problems and the noise bursts are so annoying, especially to women, that FM automobile radios have an attenuated high frequency audio response. AM stereo in the automobile will be excellent and in many parts of the country where FM stereo has reception problems, AM stereo will be far better.

CONCLUSION

The Motorola AM stereo system is the system designed to be heard. In other words, designed to be received inexpensively so that millions of radio listeners can purchase AM stereo radios. While the design is excellent for cost effective radios, it is the best overall technical performer for the broadcaster because it is capable of FM-like audio performance with full amplitude modulation capability and stereo coverage essentially the same as your present monaural coverage.

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Motorola's C-Quam® AM stereo was originally conceived as a mathematical model of a new technology communication system by the corporate research and development staff, and its worth was proven by computer analysis before anyone touched a soldering iron.

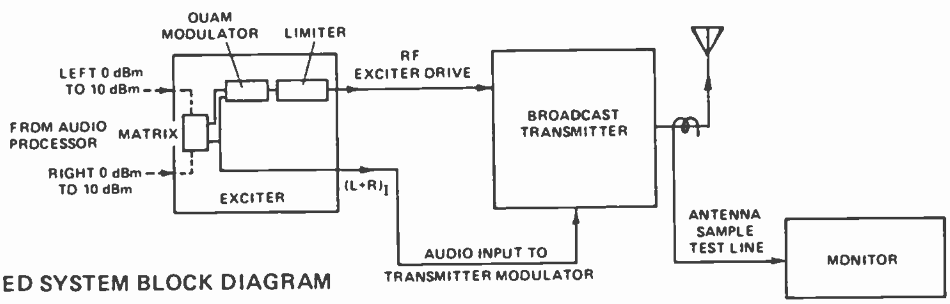
Nearly seven years passed between the original concept of Motorola's AM stereo system and the development of production hardware. Motorola corporate staff scientist, and the Modulation Systems Laboratory, began work on the technology in 1975. The basic system theory was developed in about four months, but refinements and FCC approval required an additional five years. Four other corporations competed for AM stereo system approval. However, the FCC left it up to the industry marketplace which included broadcasters, receiver manufacturers, and system proponents to resolve a system standard.

The idea of AM stereo is not new. Philco developed an experimental AM stereo system in the late fifties using quadrature modulation and tested it on WABC in New York. Also, CBS, in the early sixties, tried out a very similar system and conducted experimental transmission on WCBS also in New York.

Philco did propose its system to the FCC in the AM-FM and TV stereo proceedings in the late fifties, but the Commission rejected all AM stereo systems at that time. CBS did not pursue its system further. Concurrently, the FCC in the 1960s granted stereo capabilities only to FM radio, which was having difficulty competing with AM radio at that time. But AM radio soon began to lose ground without stereo sound. AM converted to talk because it didn't have stereo, and continued to lose market share for many years.

While Philco and CBS had been unsuccessful in implementing a compatible quadrature system, Motorola found a way to take advantage of the quadrature characteristics while still maintaining monaural compatibility. The Motorola system extracts the phase modulation component of a full quadrature signal and transmits that as the stereo information. The monaural signal is transmitted as the normal AM signal thus providing excellent compatibility with AM receivers.

The resulting Motorola C-Quam system consists of – an exciter that converts AM transmitters to stereo and a monitor that measures the results – which are both installed at the AM radio station.



SIMPLIFIED SYSTEM BLOCK DIAGRAM

The final system link is the radio receiver (introduced in 1983) incorporating the Motorola MC13020 C-Quam AM stereo decoder integrated circuit.

WHAT IS C-QUAM?

C-Quam is a system using amplitude modulation for the main (L + R) signal, and a quadrature type of phase modulation for the stereo information. Quadrature combines two signals at a phase angle of 90 degrees for transmission, and then at the receiver separates them again. It is another form of multiplexing. This technique is used to transmit the color information in the U.S. TV color system and is used for encoding of SQ and QS quadraphonic records. In the application to AM stereo, quadrature is really transmitting two AM signals on the same channel. For relatively narrow bandwidth applications such as we have with AM radio, AM is really the most efficient emission because amplitude modulaton requires the minimum bandwidth and it is independent of noise. What this means is that in an AM receiver, the effective background noise remains the same with or without modulation. This is not so with FM or PM, which under modulation, "kicks up" additional noise not present under no modulation conditions. So in AM quadrature, an additional channel can be created and heavily modulated without "kicking up" excessive noise. In other words, for narrow bandwidth communications systems, there is a signal to noise advantage to using AM quadrature.

Another important point for AM stereo is the long transmission path from the transmitter, through a directional antenna, over a difficult propagation path, and through a narrow bandwidth and possibly mistuned receiver, is a very rough one. In order to be demodulated with the least distortion and maintaining separation, the signal must be very resilient . . . able to withstand the difficult transmission experience. This also is best done with AM quadrature because two of the same type of signals are being transmitted and therefore undergo the same type of distortions which can in many instances be canceled at the other end. In other words, for AM stereo the differences between the two signals must be preserved, and if each undergoes the identical distortions during transmission, the differences between the two signals will be maintained. This is another reason why the AM/PM and AM/FM stereo systems are not very good because distortions to the AM component are very different from the distortions to the PM or FM component during transmission, and the result is a much more distorted AM stereo signal.

Although many have tried to use AM quadrature for AM stereo, the most difficulty is encountered when modifications are made to make it compatible with envelope detectors in existing AM radios. The Motorola scientists and engineers found a way of taking advantage of the quadrature characteristics, while transmitting a compatible AM component.

THE NATURE OF AM AND FM SIDEBANDS

In order to describe the system, some basics must be understood about certain types of modulation and how it is detected or not detected. To check our understanding, let's look at two basic types of transmission, AM and FM, modulated by a very low distortion sine wave.

When a signal is amplitude modulated by a sine wave, we can describe it in several ways. One is to simply look at the amplitude and trace it vs. time. This would be the typical display on an oscilloscope of the R.F. envelope. See Figure 1. Another is to look at it on a spectrum analyzer which would show three vertical lines, in the center, a taller line representing the carrier, and the two sidebands, lesser in amplitude, shown on either side of the carrier. In these two representations, there is no phase information given but for now think of the two sidebands as being in-phase sidebands or "I" sidebands. Thus in a perfect AM signal with no distortion there are no higher order sidebands or harmonics of the primary AM sidebands and there is no net phase modulation of the total of the carrier and the two sidebands.

The other case, FM (or PM) is where the phase or frequency is modulated according to our low distortion sine wave, and let's say the deviation is at least a few kHz. In this case, the R.F. envelope does not vary and the A.C. output of the envelope detector would be zero. The spectrum, however, would usually consist of a component at the carrier frequency and a family of sidebands located at multiples of the modulating frequency away from the carrier. For instance if the carrier frequency was 1000 kHz, and the modulation was 1 kHz, there would be symmetrical sidebands at 999, 1001 and at multiples of 1 kHz that are significant.

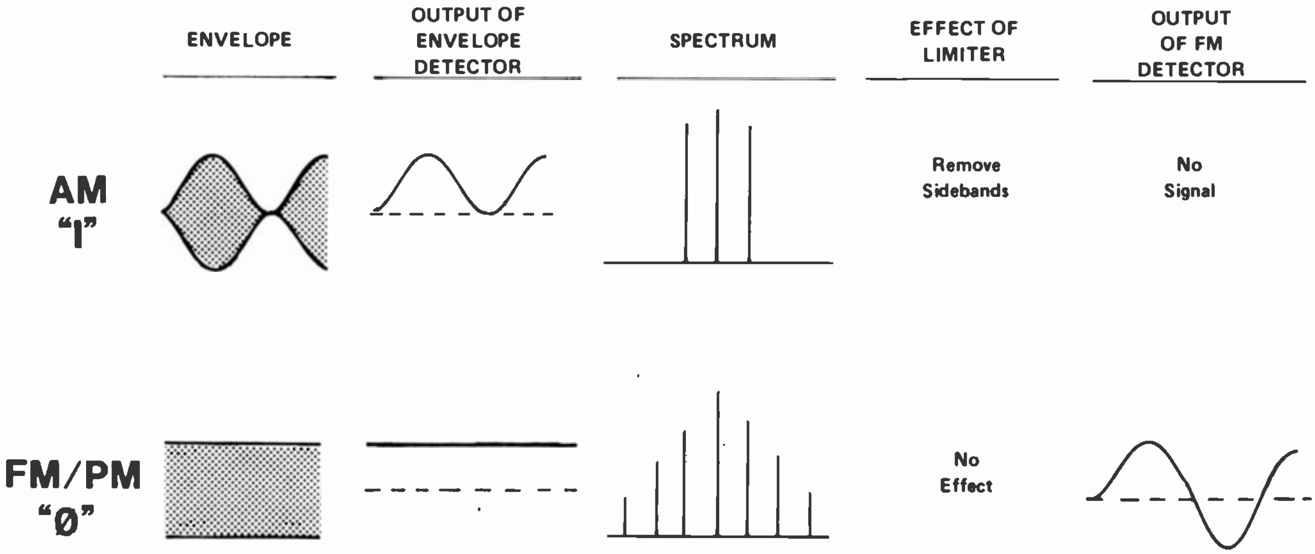


Figure 1.

If there is a carrier and sidebands, why doesn't the envelope detector detect the modulation? The reason is that in FM and PM, the instantaneous phase and amplitude of the carrier component and all the sidebands always add up to the same power as the unmodulated carrier. As the modulation is turned up, the carrier is reduced in amplitude and the missing carrier power is given to the sidebands, but the sum total at all times remains the same. It is the phasing of the sidebands that determines whether they will add and subtract with the carrier to produce differences in amplitude or whether they will add and subtract with the carrier component to always give the same amplitude. In the case of FM or PM, let's call the sidebands phase or "Ø" (phi) sidebands.

Now, the interesting thing is that "Ø" sidebands don't need a linear amplifier to be amplified and can be crunched to death by limiters and class C amplifiers and the same spectrum still comes out the other end. On the other hand "I" sidebands must have linear amplification in order to survive and can be totally stripped from the signal by a good limiter. An envelope detector will be blind to the existence of perfect PM or FM sidebands, and a phase or frequency demodulator will not see perfect "I" sidebands or amplitude modulation.

Another interesting fact is that all modulation can be represented by a combination of the "I" sideband components and the "Ø" sideband components. This is very important in AM stereo broadcasting because it is necessary to split any of the AM stereo system's signals into the "I" and "Ø" signals for transmission on an existing AM transmitter. See Figure 2. For all systems, the "I" signal is given to the transmitter in audio form at the audio input to the transmitter and then it amplitude modulates the signal in the normal way recreating an AM or an "I" sideband signal. For all systems, the "Ø" components are fed to the transmitter in R.F. form as a phase modulated signal that replaces the crystal oscillator in the transmitter. Of course the "Ø" signal sidebands can pass through the intermediate and final amplifier R.F. stages of the transmitter even though these stages are non linear and usually operate class C. The Motorola AM stereo system also required that it be reconstructed for such transmission but certain modifications are made for compatibility with the millions of existing AM radios.

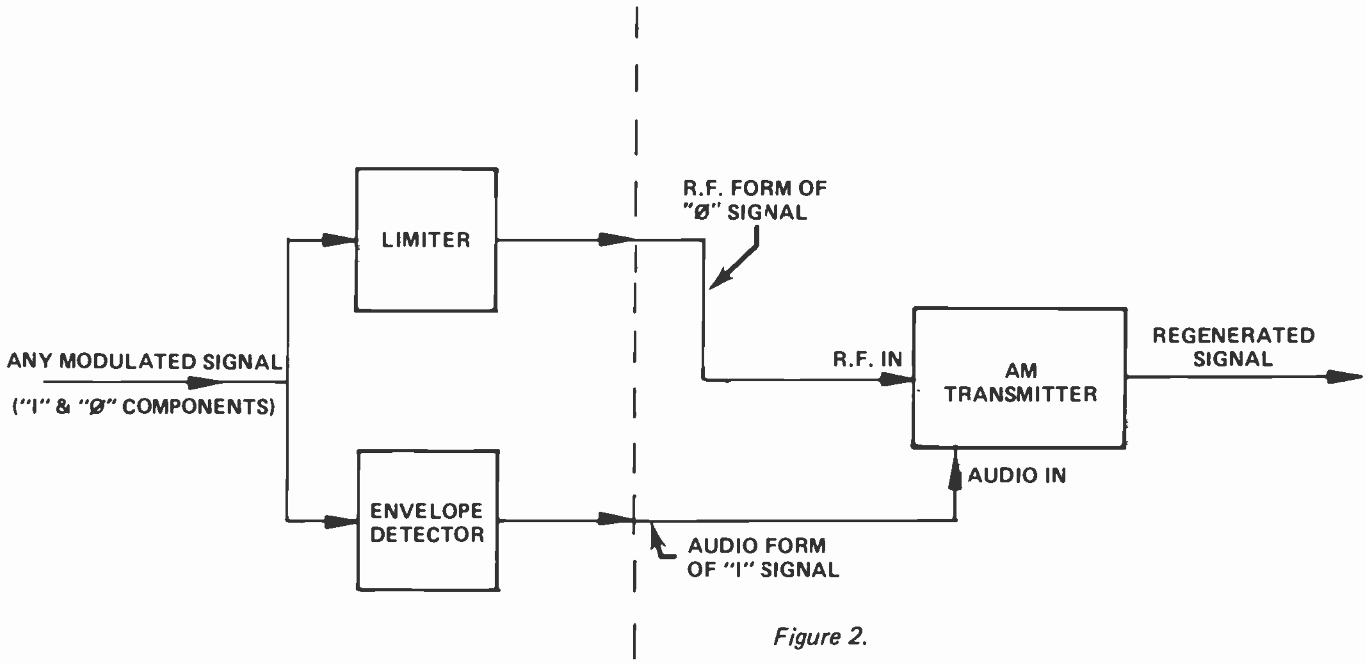


Figure 2.

PURE QUADRATURE

Observe Figure 3. Pure AM-AM quadrature can be generated by two transmitters connected so that their outputs add. One transmitter would be a standard AM generator producing the carrier at, let's say, zero phase, and sidebands associated with that carrier ("I" sidebands). A second transmitter is fed from the same master oscillator as the AM transmitter, but the phase is shifted 90 degrees. Because we already have a full carrier at zero degrees phase from the AM transmitter providing a phase reference for the receiver, the second transmitter does not need a carrier and is set up with a balanced modulator canceling out the carrier and producing only sidebands. Because these sidebands are generated from a carrier which is 90 degrees out of phase from the AM transmitter, these sidebands will be 90 degrees out of phase with the AM sidebands and "in quadrature." These become our "Q" sidebands.

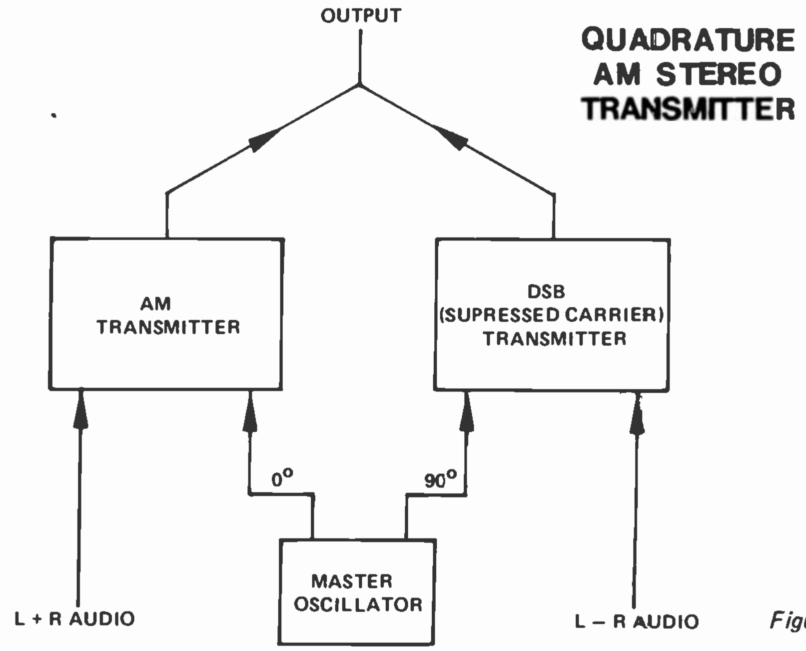


Figure 3.

If we wanted to make an AM stereo system we could transmit L + R into the AM transmitter, and L – R into the double sideband transmitter. Sounds good, but under left or right only conditions where both transmitters are contributing sidebands to the output, the resultant would be a distorted AM signal. Before we look at why, let's take a look at a quadrature demodulator which is also the widely touted synchronous detector.

THE QUADRATURE (SYNCHRONOUS) DETECTOR

To recover the audio signals separately at the receiver, a system of phase detectors is arranged. See Figure 4. First, a reference phase must be derived from the transmitted signal. This is the refe-ence carrier which is generated by means of a phase locked loop (PLL).

The device that is primarily responsible for the operation of the synchronous detector is the balanced demodulator or product detector. When this device is given an input signal and a reference carrier, it will provide at its output the difference of the two signals. If the two signals are identical in frequency and 90 degrees out of phase, the output will be zero. If there is a constant difference in phase it will give a D.C. output or if the phase is varying it will give an A.C. output. The D.C. output of the "Q" detector is fed back to a voltage controlled oscillator (VCO) which causes the frequency and phase of that oscillator to zero in on the input carrier frequency and phase and then lock to it.

This provides the phase reference for the "I" and "Q" detectors. The A.C. output from the "I" demodulator provides the original L + R audio from the AM transmitter, but it does not see the "Q" sidebands from the double sideband transmitter. The second demodulator is also fed from the VCO but its carrier reference signal is automatically shifted 90 degrees. Therefore it sees the "Q" sidebands from the double sideband transmitter and sees nothing from the AM transmitter input audio which is L + R.

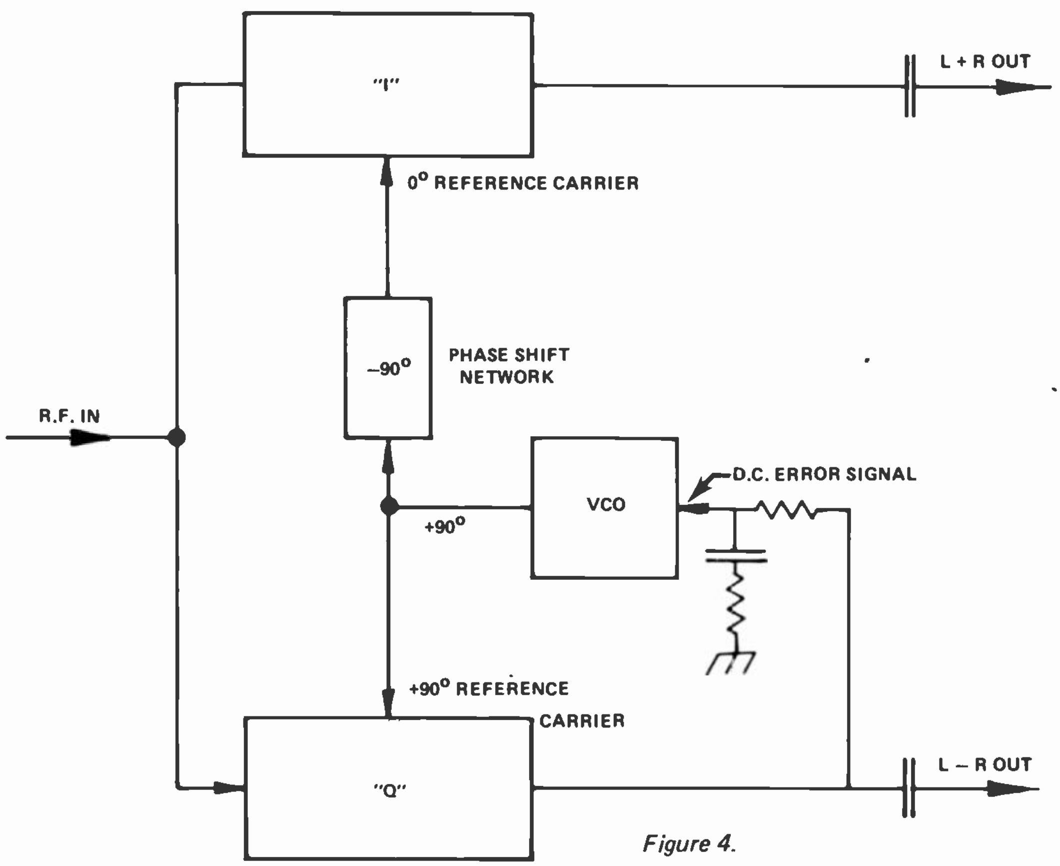


Figure 4.

The AM-AM quadrature system would be excellent for AM stereo except that the envelope detectors in normal AM radios don't see only the "I" sidebands or the "Q" sidebands but see the simple vector addition of both. The envelope detector is not capable of seeing any phase information and only sees the RMS total of the modulation and carrier regardless of phase.

Under L + R (L = R) only modulation conditions (monaural), there is no problem, because only the AM transmitter is modulated and the envelope detector recovers AM perfectly. (The double sideband stereo transmitter receives no audio because when L = R, L – R = 0.) However, under stereo conditions, for instance, when L only is transmitted, full sideband components are contributed by both the AM and double sideband transmitters and the envelope looks like Figure 5. This would not be compatible with existing envelope detector receivers and a very distorted signal would be heard.

QUADRATURE MODULATION ENVELOPES

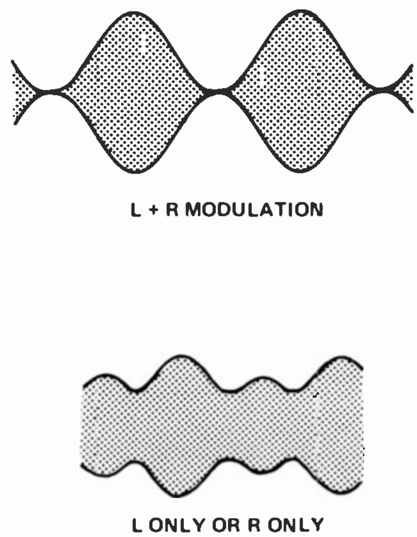


Figure 5.

COMPATIBLE QUADRATURE

The Motorola AM stereo system is not complicated at all. It simply takes a pure quadrature signal as just described, and extracts the phase modulation components of the quadrature signal and phase modulated the broadcast transmitter. At the same time it sends L + R audio to the audio input of the transmitter as usual. That's it! The advantage is that a very nice AM signal is always transmitted so that the envelope detectors are compatible, but that the phase modulation of the carrier is derived from a pure quadrature modulation. The result is a signal with most of the advantages of quadrature modulation while maintaining all important monaural compatibility.

THE C-QUAM ENCODER

The C-Quam encoder is diagramed in Figure 6. Note that pure quadrature is generated by taking L + R and L – R and modulating two balanced modulators fed with R.F. signals out of phase by 90 degrees. In this case the 90 degrees phase shift is derived by using a Johnson counter which divides an input frequency (four times station carrier frequency) by four and automatically provides digital signals precisely 90 degrees out of phase for the balanced modulators. The carrier is inserted directly from the Johnson counter. At the output of the summing network, the result is a pure quadrature AM stereo signal. From there it is passed through a limiter which strips the incompatible AM components from the signal and leaves only the phase modulation "Ø" sidebands. This is not the same as the simple output of the "Q" modulator because the addition of the "I" and "Q" balanced modulators produced some phase shifting not present in the "Q" modulator alone. The output of the limiter is amplified and sent to the broadcast transmitter in place of the crystal oscillator.

The left and right audio signals are precisely added and sent to the audio input terminals of the broadcast transmitter.

That's the essence of the Motorola C-Quam encoder.

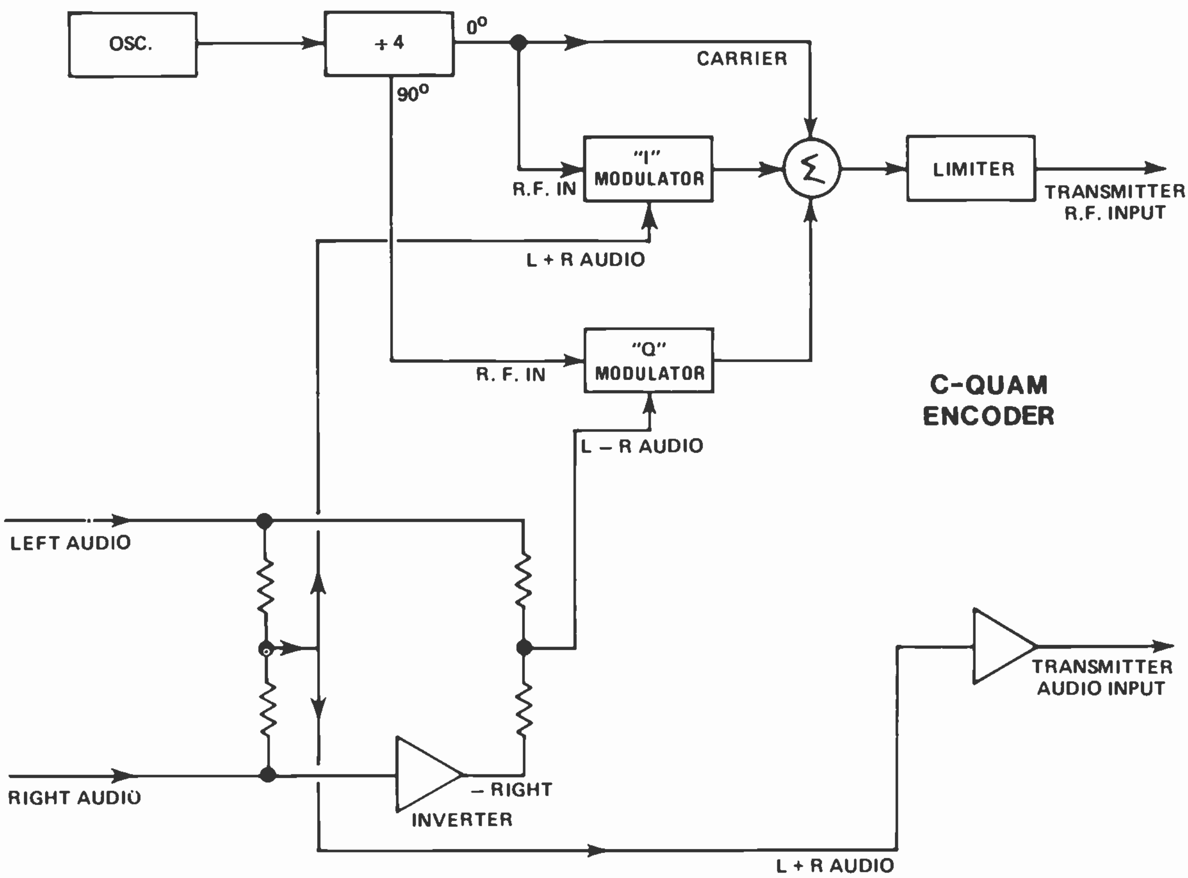


Figure 6.

DECODING C-QUAM

C-Quam is decoded by simply converting the broadcast signal which is already "almost" quadrature to quadrature and then using a quadrature detector to extract L – R. Refer to Figure 7. Note that the demodulator contains a section which is the pure quadrature demodulator as previously described. In order to prepare the broadcast signal for the quadrature demodulator, it has to be converted from the envelope detector compatible signal which is broadcast, to the original quadrature signal that was not envelope detector compatible. This is done by demodulating the broadcast signal two ways; with an envelope detector, and with an "I" detector. The two signals are compared and the resultant error signal is used to gain modulate the input of the "I" and "Q" demodulators.

When the transmitted signal is L + R (monaural, no stereo) the transmitted signal is pure AM or only "I" sidebands. In this case the envelope detector and the "I" demodulator see the same thing. There is no error signal, the gain modulator does nothing and the signal passes through without change. However, when a left or right only signal is transmitted, both AM and PM is transmitted and the input signal is shifted in phase to the "I" demodulator and loses some of its "I" amplitude. The envelope detector sees no difference in the AM because of the phase modulation, and when the envelope detector and the "I" demodulator are compared, there is an error signal. The error signal AGC's the input level to the detector. This action makes the input signal to the "I" and "Q" demodulators look like a pure quadrature signal and the "Q" audio output gives a perfect L – R signal. The demodulator output is combined with the envelope detector output in a matrix to give left and right audio outputs.

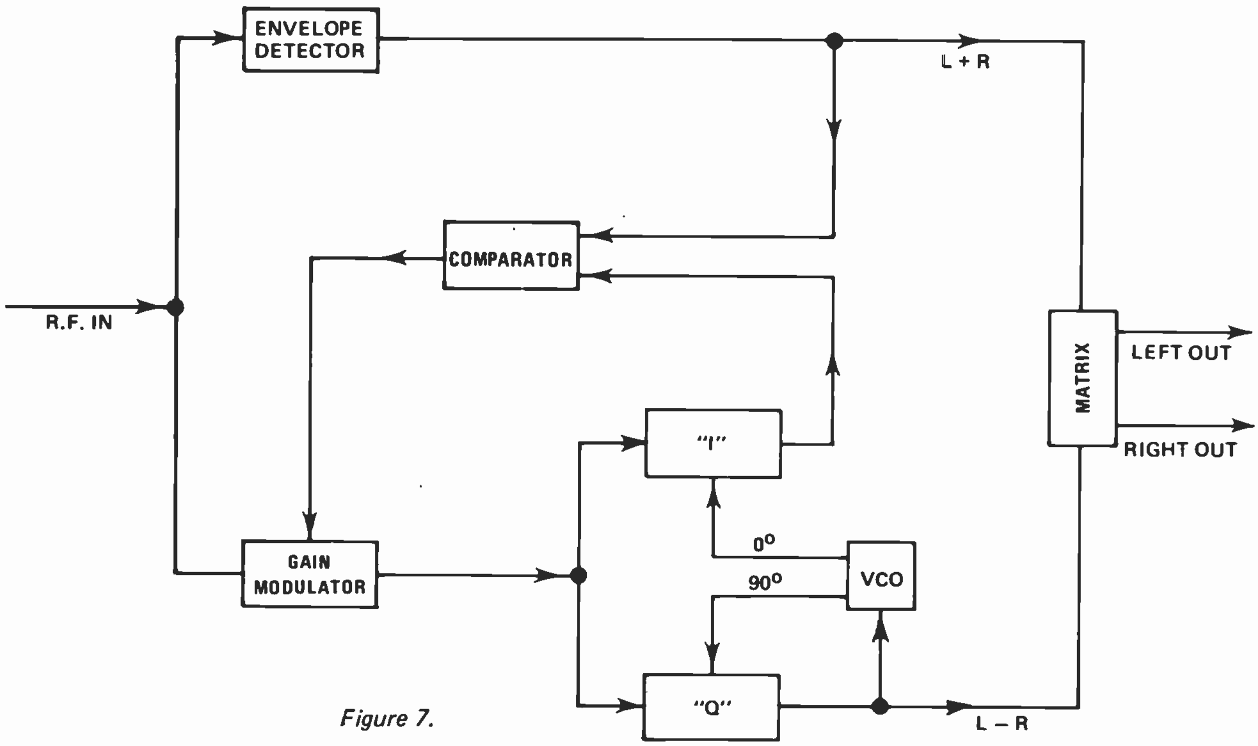


Figure 7.

SYSTEM PERFORMANCE UNDER HEAVY MODULATION

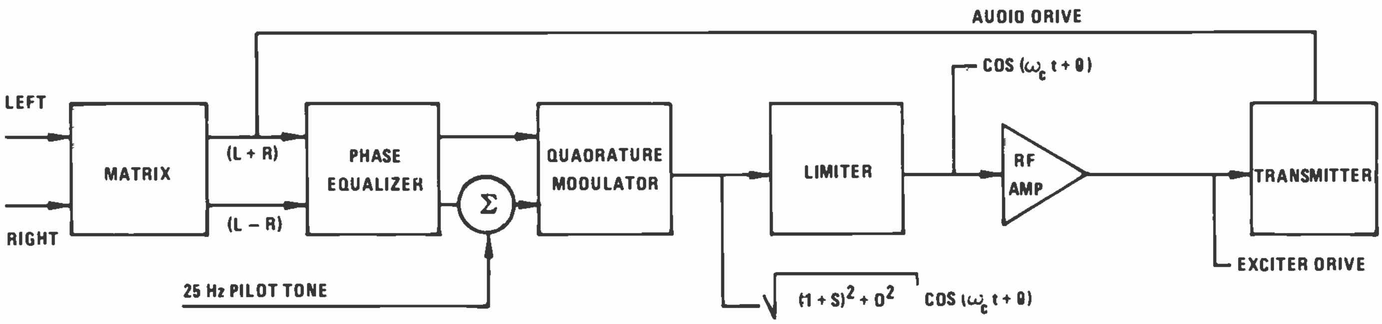
There are many advantages of the Motorola system. One is its performance under 100 percent negative amplitude modulation conditions. When the carrier momentarily becomes small as in 100 percent negative modulation, the output of the envelope detector also becomes small. Because of the action of the comparator and gain modulator, the output of the "I" demodulator is small. Simultaneously, the output of the "Q" demodulator also is forced to be small. This means that there will be no large noise popping from the stereo channel under heavy negative amplitude modulations.

APPENDIX

The following is a more detailed mathematical description of the C-Quam system.

ENCODING COMPATIBLE QUADRATURE MODULATION

The existing RF oscillator of the transmitter is replaced by a substitute reference which has the angular modulation of a quadrature signal. The existing AM modulation technique is basically unchanged.



Note that the audio modulation sum information is unchanged from the monaural case and that a quadrature phase modulated RF drive is substituted for normal RF drive. The only other change is the presence of a Phase Equalizer to compensate for the differences in Amplitude/Phase relationships between the audio signal path and the RF path. This is necessary to maintain separation over a wide bandwidth.

Any suitable stereophonic audio processors may be used.

DECODING THE COMPATIBLE QUADRATURE SIGNAL

The received compatible quadrature signal is a quadrature signal which has been modulated by the cosine of its relative phase angle information. It is also a compatible envelope detector signal. Therefore, sum information may be decoded with either an envelope detector or with a synchronous detector that is inversely modulated by the cosine of the phase modulation. Difference information may be decoded with a synchronous quadrature demodulator which is in inversely modulated by the cosine of the phase modulation. In fact, there exists a multiplicity of decoding methods since:

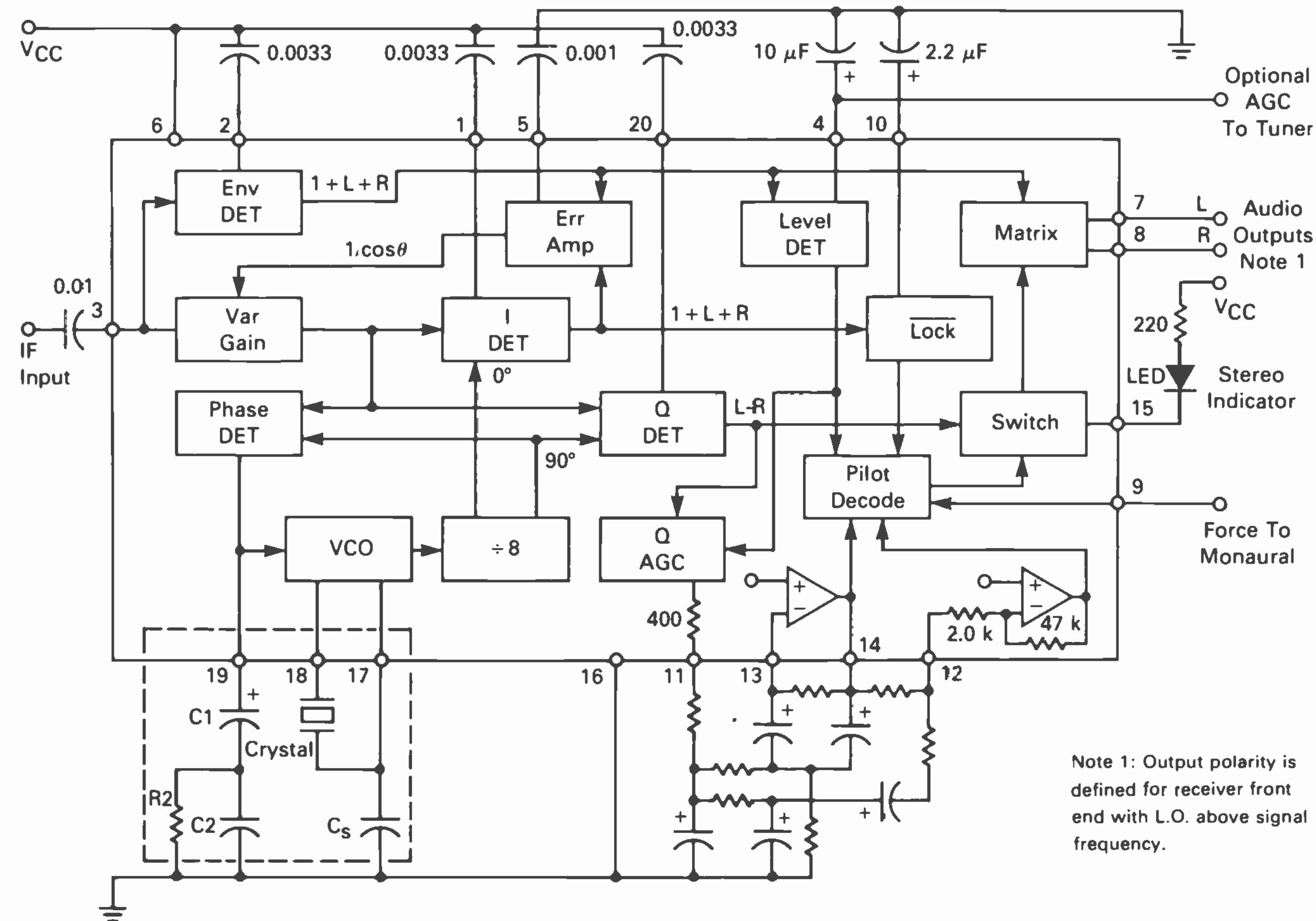
$$L - R = (1 + S)\tan\theta = \frac{(1 + S)\sin\theta}{\cos\theta}$$

Where: $S = L + R$

Hence, any sequence of operations which results in L − R is a valid decoding algorithm. Even non-PLL decoders are allowed since a discriminator, integrator, tangent function sequence results in L−R.

Motorola has evolved a first generation decoder design already discussed, which maximizes performance benefits at a minimum of cost and adjustments. Second and third generation decoders are under development which will further advance the state of the art.

PRESENT C-QUAM RECEIVER DECODER IC



Note 1: Output polarity is defined for receiver front end with L.O. above signal frequency.

SIGNAL EQUATION FOR MOTOROLA COMPATIBLE QUADRATURE SYSTEM

$$E_c = A_c\,(1 + M_s\,(L(t) + R\,(t))\cos\left[\omega_c t + \tan^{-1}\left\{\frac{M_d\,(L\,(t) - R\,(t)) + .05\sin 50\pi t}{1 + M_s\,(L\,(t) + R\,(t))}\right\}\right]$$

where: M_s = index of modulation for sum information
M_d = index of modulation for difference information
.05sin $50\pi t$ = 25 Hz. pilot tone.

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