A DOUBLE SIDEBAND-QUADRATURE CARRIER MULTIPLEX TELEMETRY SYSTEM[1]

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Summary A novel FDM telemetry technique was developed consisting of a double sideband-quadrature carrier multiplexing system (DSB-QCM). Each subchannel in the DSB-QCM system carries two completely overlapping DSB data signals, one double-sideband modulated on the subcarrier itself, and the other on a quadrature version of the subcarrier. Demodulation with cophasal and quadrature subcarriers enables simultaneous data extraction from each channel within acceptable distortion levels. The feasibility and practicability of such a DSB-QCM telemetry system is discussed in this paper. Crosstalk levels between the quadrature multiplexed channels were measured and guardband requirements between adjacent channels were assessed for a modem comprised of three pairs of DSB-QCM channels. Crosstalk levels between uniformly loaded DSB -QCM channels were below 2% and guardband requirements equivalent to conventional DSB systems were observed. The DSB-QCM performance was also examined as a function of input SNR with two competing subcarrier synchronization methods. Subcarrier synchronization by means of synthesized reference tones coherently derived from a single pilot was demonstrated to be superior in The presence of noise to a channel reference approach in which each data channel must synchronize its own subcarrier. The major conclusion from this investigation is that DSB-QCM/FM telemetry combines the advantages of both SSB/FM and DSB/FM by accommodating as many data channels as SSB/FM but with low distortion data processing and the dc data response characteristic of DSB/FM.

Introduction Efficient utilization of available bandwidth and low-distortion data processing are fundamental objectives in the evolution of improved frequency division multiplex (FDM) techniques meeting the demands of high data-density, high data-quality telemetry systems. A novel multiplexing technique is described having the advantages of both DSB/FM and SSB/FM telemetry systems but without their corresponding disadvantages. The technique, called double sideband-quadrature carrier multiplexing (DSB-QCM), operates as follows: each subchannel carries two data signals, one double sideband modulated on the subcarrier itself, and the other on a quadrature version of the

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subcarrier. Thus the same degree of bandwidth utilization efficiency is achieved as with SSB/FM, but with low data distortion and the dc response characteristic of DSB/FM.

Description of DSB-QCM Operation A simplified diagram of a single DSB-QCM modulator-demodulator channel is shown in Fig. 1. The various data signals are arbitrarily paired with signals of similar spectral properties and each signal is double sideband modulated onto subcarriers 90° apart in phase. Let the two data signals in a DSB-QCM pair be represented as $d_{ic}(t)$ and $d_{iq}(t)$, where the subscript integer i designates the channel number and the subscripts c and q identify the data modulated on the cophasal and quadrature channel, respectively. An arbitrary subcarrier signal is chosen, which can be represented as $\cos \omega_i t$. Now, $\cos \omega_i t$ is modulated by $d_{ic}(t)$ in a balanced modulator and, $\cos \omega_i t$ shifted by 90°, is modulated in a similar manner by $d_{iq}(t)$. The double sideband modulated signals are added, then filtered to remove the spectral region centered around $2\,\omega_i$. The resulting double sideband-quadrature carrier multiplexed (DSB-QCM) signal can be written as

$$g_i(t) = d_{ic}(t) \cos \omega_i t + d_{iq}(t) \sin \omega_i t$$

All other subcarrier signals are similarly modulated and summed to yield

$$\begin{aligned} G(t) = \sum_{i=1}^{N} g_i(t) &= d_{1q}(t) \sin \omega_1 t + d_{1c}(t) \cos \omega_1 t \\ &+ d_{2q}(t) \sin \omega_2 t + d_{2c}(t) \cos \omega_2 t \\ &+ \dots \\ &+ d_{Nq}(t) \sin \omega_N t + d_{Nc}(t) \cos \omega_N t \end{aligned}$$

where G(t) is the composite FDM baseband signal and N is the total number of data channels normally accommodated in conventional DSB systems. Figure 2 shows a representative data signal spectrum and the composite G(t) spectrum made up of cophasal and quadrature parts. Two data channels occupy overlapping spectral regions and hence 2N DSB data channels are frequency (and phase) division multiplexed. The spectrum of G(t) contains the same number of data channels as a SSB multiplexed baseband accommodating data with similar spectral characteristics.

If B is the one-sided bandwidth of each data signal, the spectrum of GM will not contain any subchannel overlap between adjacent QCM channels if the spacing between the subcarriers is slightly greater than 2B. The composite modulating signal, defined as M(t), is made up of G(t), plus the pilot reference tone, at an rms level of E_p, from which all subcarriers are derived. The composite baseband signal , M(t) is then applied to a standard FM transmitter whose design requirements are consistent with the FM transmitter accommodating other telemetry baseband signals.

The DSB-QCM/FM signal is received by a conventional FM telemetry receiver. After discrimination or phase-lock detection in the FM demodulator portion of the receiver, the pilot reference tone is extracted and the various subcarriers are coherently synthesized and fed to the subchannel demodulators. Each DSB-QCM pair is product demodulated separately with the appropriate referenced subcarriers 90° apart in phase. The two separate demodulator outputs are lowpass filtered to recover the data signals $d_{ic}(t)$ and $d_{iq}(t)$. It is interesting to note that predetection channel selective filtering is not required at the demodulator although some bandpass filtering may be used. The lowpass postdetection filtering provides the required subchannel selectivity.

Main concern in the demodulation operations is the extraction of each data message with minimum crosstalk between the overlapping quadrature multiplexed data signals. Let the subcarrier oscillator voltage at the

$$e_{osc}(t) = \cos(\omega_i t + \phi_{osc})$$

The amount of crosstalk in the demodulator output depends on the phase error between ϕ_{osc} and the phase shift, ϕ_{si}, on the input subcarrier. The small nonzero error, $\phi_\epsilon = \phi_{osc} - \phi_{si}$, is a random fluctuation due to tape recorder flutter or noise. The PLL controlled local oscillator signal multiplies G(t) to produce in the lowpass filtered output of each demodulator channel of Fig. 1

$$\begin{aligned} e_{ic}(t) &= d_{ic}(t)\cos\phi_\epsilon + d_{iq}(t)\sin\phi_\epsilon \\ &\approx d_{ic}(t) + \phi_\epsilon d_{iq}(t) \end{aligned}$$

and

$$\begin{aligned} e_{iq}(t) &= d_{ic}(t)\sin\phi_\epsilon + d_{iq}(t)\cos\phi_\epsilon \\ &\approx d_{iq}(t) + \phi_\epsilon d_{ic}(t) \end{aligned}$$

Thus, the crosstalk between the pair of QCM channels is directly proportional to the phase error, for $\phi_\epsilon << 1$ radian. If we assume a high signal-to-noise ratio in the closed loop bandwidth of the PLL which controls the subcarrier phase then the rms value of the phase error is approximately

$$\overline{\phi_\epsilon^2} = \sigma_\phi^2 \approx \frac{1}{2(S_p/N_{c\ell})}$$

for $(S_p/N_{c\ell}) > 10$ dB. The tone power in this expression, S_p is proportional to the strength of the reference tone transmitted with the baseband signal, i.e., $S_p \propto E_p^2$. The noise in this expression is proportional to the noise power measured in the closed loop bandwidth of the PLL which isolates the pilot reference tone from which the subcarriers are synthesized. This noise is due to tape recorder flutter or additive noise in the case of an RF input signal level near threshold.

The ratio of crosstalk power to the data signal power between any pair of quadrature multiplexed channels is given approximately by

$$\frac{P_{cross,i}}{P_{sig,i}} = \frac{\overline{d_{ic}^2(t)\,\phi_\epsilon^2}}{\overline{d_{iq}^2(t)}} = \frac{\overline{d_{ic}^2(t)}}{\overline{d_{iq}^2(t)}}\;\frac{1}{2(S_p/N_{c\ell})}$$

Note that the crosstalk to signal power ratio is dependent upon the relative power ratio of the data signals in each channel and the signal to noise ratio in the subcarrier PLL. For the case where the channel loading is such that the power levels of the data in paired channels are essentially equivalent, then, the crosstalk ratio depends mainly upon the subcarrier SNR given by $\frac{1}{2}(S_p/N_{c\ell})$. The subcarrier SNR depends upon several factors some of which are within the control of the designer. By assigning sufficient power, S_p, to the transmitted reference tone, the crosstalk ratio can be reduced. However, an increase in power level assigned to the reference tone reduces the power allocated to the data channels for a given constraint on total rms level, typical of deviation constrained FM telemetry systems.

The crosstalk power can also be minimized by narrowing the closed loop noise bandwidth of the phase-locked loop. However, a minimum bandwidth is usually dictated by other factors not under the control of the designer such as tape recorder flutter, doppler effects and stability considerations. These factors dictate wider PLL bandwidths than would otherwise be necessary, and, as a result, $S_p/N_{c\ell}$ is determined accordingly.

Implementation of a DSB-QCM Test Modem A DSB-QCM modulator-demodulator (modem) was implemented to demonstrate the feasibility of the quadrature multiplex technique. The test modem appears in Fig. 3 with the corresponding block diagram in Fig. 4. Provisions for operation as a conventional DSB system were included in order to facilitate comparison measurements between DSB-QCM and DSB systems. The implementation of the DSB-QCM system also included provisions for two different subcarrier synchronization modes. The first, identified as the channel reference tone (CRT) sync mode, requires transmission of reference tones in each subchannel. Individual phase-locked loops derive phase information from the reference tones to synchronize the subcarriers. The second sync mode, identified as the synthesized reference tone (SRT) sync mode, requires transmission of a single pilot tone. A phase-locked loop at the demodulator locks to the pilot tone and synchronizes a local oscillator from which all subcarriers are coherently synthesized and delivered to the respective subchannel demodulators in the proper phase. With either sync mode, provisions are also usually included to resolve data polarity ambiguities at the demodulator resulting from frequency division operations in deriving subcarriers. This requires transmission of a master reference tone in addition to the pilot or channel reference tones.

The DSB-QCM test modem is comprised of six independent telemetry data channels multiplexed on quadrature versions of three adjacent subchannel carrier frequencies of 40 kHz, 48 kHz, and 56 kHz, respectively. The bandwidth of all subchannels was 2.5 kHz as determined by the modulator input and demodulator output lowpass filters. The channel reference tone frequency (used only when operated in the CRT sync mode) was 3 kHz for all channels. A master reference tone was also transmitted (in both sync modes) at 3 kHz as part of the baseband. When operated in the SRT sync mode a pilot tone was also transmitted at 192 kHz.

Accommodations for varying the subcarrier frequencies of the 40 kHz and 56 kHz subcarriers were included in the implementation to facilitate the variable guardspace measurements. These tests were conducted for both the CRT and the SRT sync mode with provisions for injecting an external subcarrier signal at the modulator for the variable frequency guardspace tests. The modem design allowed for overlap among all three DSB-QCM channels as well as separations of the channels by as much as 12 kHz spacing between the subcarriers.

Automatic gain control provisions were implemented with the modem. An AGC circuit in the modulator regulated the average level of the composite baseband signal by means of incoherent AGC. The demodulator contained two coherent AGC circuits; a baseband preregulator and a channel regulator. The baseband preregulator derived AGC control coherently from the 3 kHz master reference tone which was transmitted in both sync modes of operation. The channel regulator was operational only in the CRT sync mode. In this mode AGC control was derived from the channel reference tones thus ensuring gain standardization for each channel. As determined in subsequent measurements, the master pilot regulator, by itself, was sufficient for maintaining level calibration in the demodulator for both sync modes of operation.

Spurious-free modulator and demodulator multiplier circuits were designed. These circuits were driven at low signal levels to ensure the required linearity. Reduction of the spurious output level from the modulator multiplier relaxed channel bandpass filter requirements. Consequently, channel bandpass filters consisting of two pole networks with an overall 3 dB bandwidth of 15 kHz provided adequate selectivity for the system. The alignment of these filters was crucial to minimizing crosstalk between the pair of quadrature multiplexed DSB signals modulated on the same subcarrier.

The phase-locked loop circuits in the demodulators were straightforward in design. The closed loop noise bandwidth of the phase-locked loop was approximately 100 Hz as determined by a simple second-order closed loop response. The subcarrier PLL's in the CRT mode consisted of a double-loop design to extract subcarrier information from the 3 kHz sidebands transmitted in only one of the DSB-QCM channels. Provisions were not included in this modem for resolving phase ambiguities resulting from frequency division in the demodulator subcarrier circuitry. The phase ambiguity detail was not important for the demonstration of feasibility.

DSB-QCM Performance The performance of the DSB-QCM system was evaluated with the test setup of Fig. 5. The dependent variable in the tests was the total attendant distortion, expressed as SNR, which accompanied the tone in the output of a demodulator channel. The output SNR of the tone modulation was measured as a function of several independent variables such as signal-to-noise ratio (SNR) at baseband, SNR at RF, guardspace separation, channel loading and modulation. The test objectives were to determine: the levels of crosstalk between the various multiplexed channels attributable to the quadrature carrier multiplex mode of operation, the guardspace requirements for DSB-QCM data multiplexing, and to compare performance of the DSB-QCM to other telemetry multiplex systems, viz., conventional DSB.

All performance tests were made with the cophasal channels loaded with independent noise sources and each quadrature channel loaded with a tone in the 0 to 2.5 kHz region. Incommensurate frequencies were chosen for the various tone modulations. Tests were conducted first on a single DSB-QCM channel, i.e., a pair of quadrature DSB channels, followed by measurements on three DSB-QCM channels. Performance of the DSBQCM was evaluated with operation in two modes of subcarrier synchronization, the channel reference tone (CRT mode), and the synthesized reference mode (SRT mode).

Crosstalk Measurements The curves of Figs. 6, 7 and 8 are spectral density plots of the demodulated DSB-QCM output channels as plotted with a low frequency spectrum analyzer. The channel loading consisted of noise in the cophasal channel with a sinusoidal tone in the quadrature channel. The spectrum analyzer bandwidth for these tests was approximately 10 Hz wide with a frequency response having the shape of the main spike in Fig. 6. The spectral density curve of Fig. 6 was plotted for the system with the preregulator AGC disconnected and without any channel bandpass filtering in the modulator in order to reduce the noise floor in the tone channel as much as possible. This was desirable in order to detect harmonic distortion effects and other discrete frequency anomalies such as subharmonics of the channel reference tone. The system was operated in the channel reference tone subcarrier sync mode for these tests since the channel reference tone on the edge of the data skirts constitutes a more stringent test condition than if the system were operated in the synchronized reference tone mode.

The plot of Fig. 6 shows the 220 Hz data tone in the output at the 0 dB reference level. The total noise power in the cophasal channel was made equal to the power level of the tone in the quadrature channel. The noise floor in the quadrature channel output was 69 dB below the tone as measured in a 10 Hz bandwidth. The spectral density level of the noise corresponds to a total output noise level 45 dB below the tone level as measured with a power meter in the LPF output. This was the best achievable crosstalk performance for the DSB-QCM system.

The second harmonic of the 220 Hz data tone is evident at the frequency of 440 Hz which is 61 dB below the fundamental tone. Some of this harmonic distortion was attributed to the oscillator which provided the tone. The low level harmonic distortion was indicative of the good linearity in the modulator and demodulator multiplier circuits.

The spikes at 1050 Hz and 630 Hz were identified as third and fifth subharmonics of the 3 kHz channel reference tone which was modulated on the cophasal carrier. This was confirmed by moving the channel reference tone slightly and observing corresponding shifts in the frequency location of the subharmonics of the reference tone.

The power spectral density of the quadrature tone channel was replotted with all AGC circuits operative and with the modulator subchannel bandpass filters included. The test was conducted with the system in the CRT sync mode and the test results appear in Fig. 7. The effect of the AGC and bandpass filters raises the noise floor, in the region below 500 Hz, to a level of -51 dB below the power in the tone. The elevated noise floor explains why the residual levels of crosstalk were higher when AGC and bandpass filters were included. The total power level of the crosstalk, as measured in a lowpass filter bandwidth of 2.5 kHz, was approximately -35 dB below the tone level. This level constitutes an upper bound for the system with regard to crosstalk SNR. The principal factor affecting the crosstalk was the AGC which produced noise sidebands in the vicinity of the tone frequency. The mechanism generating these sidebands was amplitude modulation of the 220 Hz tone by the low frequency noise in the cophasal channel. Other factors contributing to an increase in crosstalk level were related to the alignment of the channel bandpass filter in the modulator.

The power spectral density of the corresponding noise-loaded cophasal channel is plotted in Fig. 8. The noise spectral density in this channel, as measured in a 10 Hz analyzer bandwidth, averages about the -24 dB level. The total noise power in the 2.5 kHz lowpass bandwidth is thus at the 0 dB level equal to the tone power level in the quadrature channel. It may be noted that crosstalk and harmonics due to the 220 Hz tone in the quadrature channel are sufficiently below the level of noise in the cophasal channel and were not detectable.

The spike on the skirt of the cophasal noise power spectral density plot is the channel reference tone at 3 kHz which is transmitted with the cophasal channel. This tone is not transmitted in the quadrature channel which explains for its absence in the curves of Figs. 6 and 7.

Low Frequency Intermodulation Intermodulation between the DSB-QCM channels was measured with a 1 kHz tone in the quadrature channel and a variable low frequency tone in the cophasal channel. The intermodulation appeared in the form of low frequency amplitude modulation on the 1 kHz tone in the quadrature channel. The dependence of this intermodulation upon the frequency of the variable tone is illustrated in Fig. 9 which plots the intermodulation sideband level, referred to the level of the I kHz tone vs the rate of the low frequency tone modulation in the cophasal channel. For tone frequencies 100 Hz and above, the intermodulation SNR is constant at 39 dB but dips to a minimum of 27 dB for tone frequencies of 1 Hz in the cophasal channel. The mechanism causing the increased intermodulation was attributed to the AGC amplifier which regulates the level of the composite signal of all channels in the modulator. Additional sources of low frequency intermodulation were the channel AGC amplifier in the demodulator, controlled in accordance with the level of the received channel reference tone. The AGC cut-off regions fall below 100 Hz and consequently the AGC responds to the low frequency modulation in the cophasal channel. The effect is that the AGC acts as an amplitude modulator which modulates the quadrature channel data with the low frequency cophasal data and vice versa.

The measurements indicate that the low frequency AGC limitations can affect transmission of good quality low frequency DSB-QCM data. The AGC in DSB-QCM systems must be designed, therefore, to prevent the low frequency intermodulation effects, but, must still be fast enough to allow the system to respond to relatively rapid changes in data characteristics and channel loading.

Baseband Noise Tests The results of baseband noise tests on the three channel DSB-QCM modem are shown in Fig. 10. Comparison of the DSB-QCM is also made with operation as a conventional DSB system. Noise performance was measured for each system with subcarrier synchronization provided by both the synthesized reference tone (SRT mode) and the channel reference tone (CRT mode). In all tests output SNR was measured for the tone modulation with the orthogonal channel in the DSB-QCM mode loaded with white noise. Output SNR was measured with a distortion analyzer (HP 330B) and therefore the effect of residual system distortion results in an upper bound in output SNR for high input SNR on all of the curves. Additive noise dominates the output SNR, however, for the lower input SNR, thus permitting evaluation of system noise performance. The input SNR indicated on the curve corresponds to the SNR at the input to the channel being monitored and is measured in a bandpass filter centered on the subcarrier and having a noise bandwidth equal to twice the lowpass filter bandwidth in the output of the demodulator.

The SNR output of the center channel is plotted in each curve with the two outboard adjacent channel subcarriers spaced 8 kHz apart. The bandwidth of all data channels was nominally 3 kHz resulting in a DSB subchannel bandwidth of 6 kHz. The outboard channels were loaded with independent noise sources for DSB operation and with noise and tones for DSB-QCM operation. The spectral density of the additive baseband noise was flat over the channel frequency regions and out beyond the frequency region occupied by the pilot reference tone in the SRT mode.

The noise performance of the modem operating as a conventional DSB and a DSB-QCM system is illustrated in Fig. 10 by curves A and B, respectively. Subcarrier sync for each mode was provided by the synthesized reference tone sync circuits. For input SNR greater than +40 dB, the output SNR for the DSB channel is +40 dB corresponding to a total distortion level of 1%. The corresponding SNR output for the DSB-QCM channel is +36 dB or a total residual distortion level of less than 2%. The increase in distortion in the DSB-QCM system is indicative of the crosstalk effects between the quadrature multiplexed channels. Further minimization of this crosstalk level is possible with improved AGC design and careful filter alignment but was not attempted in these tests.

Curves A and B merge together for input SNR below +30 dB. In this region the input additive noise dominates the output SNR. The input and output SNR are related in a one-to-one manner on this portion of the curves because of the linear detection process in demodulating DSB subcarriers. The curves, however, show a 3 dB input-to-output improvement in SNR, wherein, an input SNR of +20 dB results in an output SNR of +23 dB. This, of course, is characteristic of the 3 dB SNR gain in detecting DSB modulation. The realization of the 3 dB SNR gain in the DSBQCM mode indicates that the phase noise jitter in the subcarrier reference synthesizer PLL circuitry is negligible. Consequently the subcarrier phase noise does not contribute to an increase in crosstalk level from the orthogonal channel through the mechanism of detection with a reference subcarrier having a random phase fluctuation about true quadrature.

The SRT PLL lost lock in both the DSB and DSB-QCM multiplex modes for input SNR of -3 dB as measured in the data channel bandwidth. This threshold is dependent upon channel loading to some extent because the modulator AGC regulates the rms level of the composite baseband output of the modulator. Thus with more channels present less power is allocated to the pilot reference and the threshold should thus be raised slightly. However, slight changes in channel loading by removal of one channel, as was the case when reverting from DSB-QCM to DSB operation, caused only a slight change in pilot reference level. The threshold of the SRT PLL, thus, did not diff-er appreciably between DSB-QCM and DSB operation.

The performance of the DSB and the corresponding DSB-QCM system for the case in which subcarrier reference phases were established by the channel reference tones is illustrated by curves C and D of Fig. 10. In the DSB mode, the increase in distortion level in curve C, compared with the corresponding level in curve A, is attributable to the presence of the channel reference tone in the DSB data. The measurement in the DSB-QCM mode, however, was made on the orthogonal channel which did not contain the channel reference tone. The increase in distortion level in the DSB-QCM is attributable primarily to the increase in crosstalk due to the orthogonal noise loaded channel. It may be noted that the crosstalk for the DSB-QCM in the CRT mode is also approximately 2 dB worse than the DSB-QCM in the SRT mode. The difference was related to the channel bandpass filter alignment, which, in the CRT mode, has a greater effect upon crosstalk levels between the channels than in the SRT mode of operation. The reason for this is that in the CRT mode, the filter alignment must be symmetrical over the data bandwidth as well as on the skirts in the vicinity of the channel reference tone sideband frequencies. Departure from symmetry at the frequency of the channel reference sidebands precludes synchronization of the subcarrier reference in the proper phase for quadrature detection of the orthogonal DSB channels. Aligning the channel bandpass filters in the CRT mode was far more critical than in the SRT mode and therefore it was more difficult to minimize crosstalk from this source. The 34 dB level in the output SNR for the DSB-QCM in the CRT mode was a lower bound measured for this system. Circuit optimization and more careful filter alignment should lead to improvements approaching the 40 dB level.

In the region below input SNR of +30 dB the output SNR for the DSB-QCM in the CRT mode did not show the 3 dB SNR improvement characteristic of DSB detection as shown for the other three curves. In this region an input SNR of +20 dB resulted in an output SNR of +20 dB. The 3 dB degradation in output SNR relative to conventional DSB performance was attributable to the increased level of crosstalk between the orthogonal channels. The increase in crosstalk in this mode is due to the phase noise jitter in the subcarrier reference derived from the channel reference tones. The increased phase jitter level is a result of a poorer SNR for the channel reference tones. These tones are transmitted at a level 20 dB below the data (or 23 dB below the pilot reference tone in the SRT mode) and are used for synchronization purposes both with and without data loading. The resulting SNR of the channel reference tones, as measured in the closed loop bandwidth of the CRT PLL (which is identical to the closed loop bandwith of the SRT PLL), is impaired with a consequent increase in crosstalk level between the orthogonal channels. By increasing the channel reference tone level or narrowing the CRT PLL bandwidth, corresponding reductions were observed in crosstalk level between the channels.

The threshold of the DSB-QCM system operating in the CRT sync mode occurred for an input SNR of +9 dB. The threshold occurred at higher input SNR relative to the SRT mode because of the reduced level of the channel reference tone.

RF Noise Tests The performance of the modem in a DSB-QCM/FM system was evaluated in the presence of RF noise. In this test the DSBQCM modulator output served as a baseband modulation signal for an FM signal generator at 10 MHz. Various levels of noise were added to the FM signal at 10 MHz thus providing a range of SNR. The DSB-QCM modulated FM signal and additive noise were then demodulated by a 10 MHz FM demodulator. The IF bandwidth of the demodulator used for this test was 460 kHz and the discriminator bandwidth was in excess of 1 MHz. The FM threshold for this demodulator was measured using a sinusoidal(49 kHz) modulation with a deviation index of unity. This corresponds to the nominal subcarrier frequency and deviation index used in the subsequent constant deviation DSB-QCM/FM tests. The FM threshold occurred for a carrier input SNR of approximately +9 dB. This was an important parameter in the tests since all the data have a characteristic threshold break for input SNR of +9 dB.

Test results are presented in Fig. 11 for the DSB-QCM/FM system in the SRT sync mode. For the purpose of this test the system was operated with all AGC circuits removed in order to observe threshold effects more clearly without the obscuring effects of AGC. Constant rms deviation of the carrier was maintained by an operator. Removal of the AGC circuits led to corresponding improvements in output SNR. The results without AGC are therefore representative of DSB-QCM system performance with an improved AGC design.

The SNR output for a single DSB channel is plotted in curve A of Fig. 11. A theoretical curve is plotted in curve B confirming the experimental results to within 1 dB. The theoretical curve was plotted using the formula

$$(\mathrm{SNR})_o = \frac{1}{\alpha}\left(\frac{\Delta f}{f_{sc}}\right)^2 \left(\frac{S}{N}\right)_{\mathrm{IF,\,in}} \left(\frac{B_I}{B_s}\right)$$

where

f_{sc} = subcarrier (48 kHz)

Δf = equivalent peak deviation of sinusoid having same rms level (Δf = 48 kHz)

α = fraction of power allocated to data channel taking into account the power in pilot tone. For these computations $\alpha = 3$

$\left(\frac{S}{N}\right)_{\mathrm{IF,\,in}}$ = FM input SNR in IF bandwidth

B_I = IF bandwidth (460 kHz)

B_s = lowpass output bandwidth (2.5 kHz)

The third test in the SRT sync mode was with a DSB-QCM channel in place of the single DSB channel. The data levels were readjusted, along with the pilot tone, to produce the specified rms deviation. The power in the DSB-QCM channel equals the power in the pilot tone. However, the power in each channel of the DSB-QCM baseband is one-fourth of the total available power as compared to one-third in the case of the single DSB channel. As a result of the lower power allocation, the corresponding SNR in the DSB-QCM is down approximately 1 dB below the level for the single DSB channel. This is confirmed by curve C of Fig. 11 which shows the 1 dB dr'op. We conclude from these curves that the FM channel did not cause an increase in crosstalk level between the DSB-QCM data channels and therefore the DSB-QCM system would suffer no ill side effects when incorporated into an FM system.

The threshold measured for the FM system occurred for an input SNR of +9 dB as shown by the break in the curves. The SRT PLL lost lock for input SNR below 0 dB. Thus, the threshold for this DSB-QCM/FM system is determined by the FM link, itself, and not by DSB-QCM baseband limitations.

The fully loaded three-channel DSB-QCM modem was subjected to FM noise tests. In these tests, an adjacent channel subcarrier spacing of 8 kHz was used. All AGC circuits were operative and the deviation of the FM carrier was adjusted to 48 kHz corresponding to a nominal deviation index of unity when referred to the 48 kHz center channel. Each DSB-QCM channel consisted of a tone with noise in the orthogonal channel. The curves of Fig. 12 plot SNR output vs FM carrier input SNR for the SRT sync mode.

The SNR performance of all three channels are within one dB of each other. The SRT subcarrier PLL's lost lock for input SNR of 0 dB which is below the FM threshold for the system measured for an input SNR of +9 dB. We conclude from these threshold observations that the subcarrier PLL threshold falls below the threshold of the FM link. The residual levels of distortion, attributable to crosstalk, result in an output SNR of +35 dB. Comparison with the curves obtained without AGC again indicate that the AGC effects contribute to crosstalk in the DSB-QCM system.

Guardspace Tests Tests were conducted on the DSB-QCM modem as a function of subcarrier spacing in order to assess guardspace requirements for DSB-QCM telemetry and to determine if DSB-QCM telemetry posed additional requirements on allowable guardspace as compared with conventional DSB systems. The tests were conducted-by operating the modulator and demodulator back-to-back. The subcarrier frequency spacings of the two outboard channels were varied (symmetrically) and output SNR was plotted for the center tone-loaded quadrature channel. The center cophasal channel was loaded with noise. The outboard DSB-QCM channels were similarly loaded with tones and noise.

Guardspace requirements should be determined by the characteristics of the data and the channel filtering. The terminal-to-terminal shape of the channel filtering, for the case of input data with a flat spectral density, has the shape of the spectral density curve of Fig. 8. The filter characteristics serve as a reference in describing adjacent channel crosstalk effects, and therefore, the lowpass attenuation characteristics of the channel filters are superimposed on the curves of Figs. 13 and 14 for the center channel and for one of the adjacent channels at a 6 kHz subcarrier spacing.

SRT Mode Adjacent channel crosstalk effects for the DSB and DSB-QCM system are shown in Fig. 13 with the system operating in the SRT mode. In this sync mode the subcarrier synchronization PLL operates independently of the data channel. The distortion varies monotonically with subcarrier separation in accordance with the channel filter selectivity of the data lowpass filters in the modulator and demodulator. Overlap up to 1 kHz from both adjacent channels was possible for $SNR_o > 25$ dB in the SRT sync mode. The system was capable of operation at subcarrier spacings as low as 6 kHz with crosstalk from adjacent channels determined by the lowpass output filters.

Comparison of the DSB with the DSB-QCM system shows that the crosstalk from overlapping DSB-QCM channels exceeds, slightly, the crosstalk under similar conditions for the DSB system. The relative data levels and filtering in each case were identical. The reason for the increase in crosstalk distortion when the adjacent DSB-QCM channels were overlapping is, because in the DSB-QCM mode, the effects of four adjacent channels were observed as compared with only two in the DSB mode, hence, the relative crosstalk level was higher. Other than the crosstalk effects due to more overlapping channels, the guardspace requirements of the DSB-QCM system are essentially the same as those of the corresponding DSB system. Finally, the SNR curves level off at the residual distortion level of 37 dB in the DSB-QCM mode and 40 dB in the DSB mode. The difference in distortion level for these regions is attributable to crosstalk between the overlapping orthogonal DSB channels.

CRT Mode The guardspace performance of the DSB-QCM and the DSB system in the CRT sync mode is illustrated in Fig. 14. For subcarrier separations in excess of 7 kHz, the adjacent channel crosstalk in the CRT mode is equivalent to the crosstalk measured for the SRT mode of Fig. 13.

Crosstalk rises sharply on the curves for the CRT sync mode at 6 kHz subcarrier separation for the DSB as well as for the DSB-QCM system. The crosstalk degradation for this particular subcarrier spacing is caused by overlap between the channel reference tone sidebands of adjacent channels. The subcarrier recovery loops track all signals within the 300 Hz pull-in range of the CRT PLD s. The subcarrier CRT PLL’s maintain phaselock, therefore, except for the 300 Hz frequency band centered at 6 kHz. The effects of four rather than two overlapping adjacent channels causes a widening of this region in the DSB-QCM mode compared to that observed for the conventional DSB system.

At subcarrier spacings less than 6 kHz, the CRT PLLI s reacquire and signal quality is improved slightly with output SNR reaching a maximum of approximately 25 dB and then rolling off monotonically as the overlap increases. Two effects are responsible for data degradation at subcarrier spacings less than 5.3 kHz. The first effect is the adjacent channel data in the channel reference tone PLL band, and, the second effect is the presence of the adjacent channel reference tone in the data band. The first effect is mainly responsible for the loss of CRT PLL lock for subcarrier spacings less than 5.3 kHz.

It can be concluded from the guardspace measurements that adjacent channel crosstalk levels are less severe for DSB and for DSB-QCM systems when demodulator subcarriers are derived from a synthesized reference as opposed to a channel reference sync mode. It also may be concluded that the guardspace requirements of DSB-QCM systems are equivalent to DSB systems with the same data characteristics and subcarrier synchronization modes.

Conclusions The feasibility and practicability of Double SidebandQuadrature Carrier Multiplex (DSB-QCM) telemetry was demonstrated in theoretical and experimental studies. The general conclusion is that DSB QCM telemetry combines the advantages of both SSB and DSB baseband FDM systems. Twice as many data channels as conventional DSB systems are accommodated thus competing on an equal basis with the data handling capabity of SSB multiplexing systems. Moreover, the low distortion levels of the DSB-QCM system, as measured in tests on the DSB-QCM modem implemented for this study, are comparable with the low distortion levels characteristic of conventional DSB systems.

A DSB-QCM modem was implemented comprised of six independent telemetry data channels quadrature multiplexed on three adjacent subchannel carrier frequencies at nominal frequencies of 40 kHz, 48 kHz, and 56 kHz, respectively. The modem was provided with two competing subcarrier synchronization modes of operation. This enabled direct performance comparisons between DSB systems with individual channel subcarrier reference systems and subcarrier reference systems utilizing a separate coherent synthesizer to provide the subcarrier. Subcarrier synchronization with the synthesizer approach was shown to be superior to the independent channel reference system in all aspects of performance and is recommended, in general, for DSB-QCM as well as DSB telemetry baseband systems. This recommendation applies to all telemetry systems whose baseband bandwidth is well within the coherence bandwidth of the combined transmission medium and receiving equipment.

Comprehensive tests were conducted on the modem to demonstrate the ability to separate and demodulate the DSB-QCM channels andmaintain low distortion levels. It was shown that crosstalk distortion between pairs of DSB-QCM channels modulated on the same subcarrier was typically below 2% and is thus comparable with the distortion level of 1% for the same data channel operating in a conventional DSB mode. Crosstalk level between DSB-QCM channels was shown to be dependent upon the AGC circuits, channel bandpass filter alignment, phase-locked loop phase error and the linearity of channel processing circuits. Guardspace measurements for various degrees of separation and overlap between the three pairs of DSB-QCM channels indicated that the separation between a DSB-QCM channel was equivalent to the separation required between conventional DSB channels. Factors affecting guardspace were the same as those in DSB and SSB systems such as data spectral characteristics, data filters and tolerable levels of adjacent channel overlap distortion.

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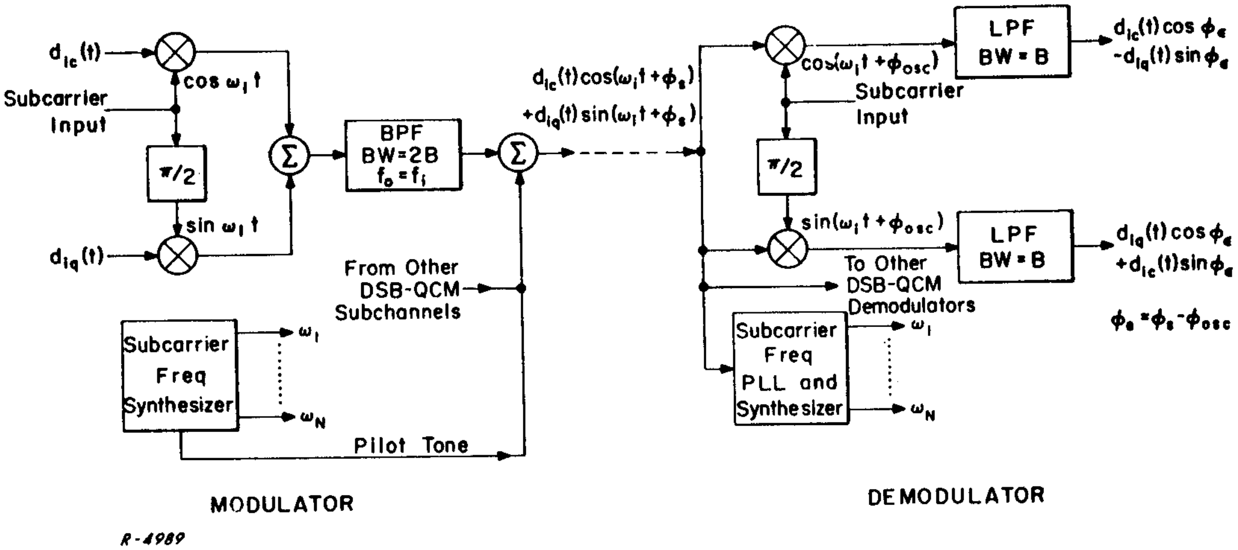

Fig.1 Simplified DSB-QCM Channel

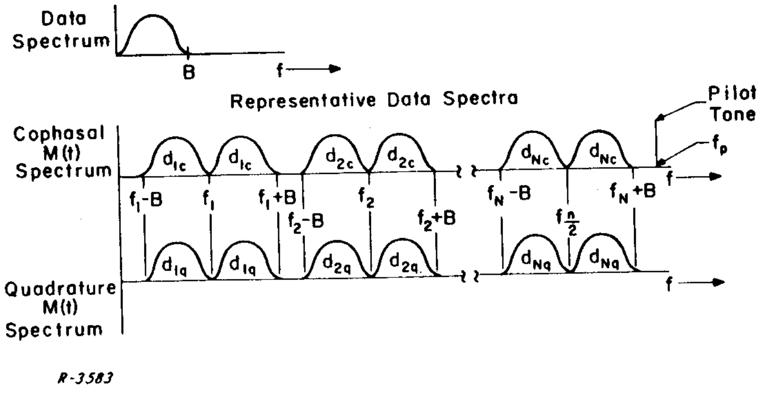

Fig. 2 Spectrum of a DSB -QCM Baseband

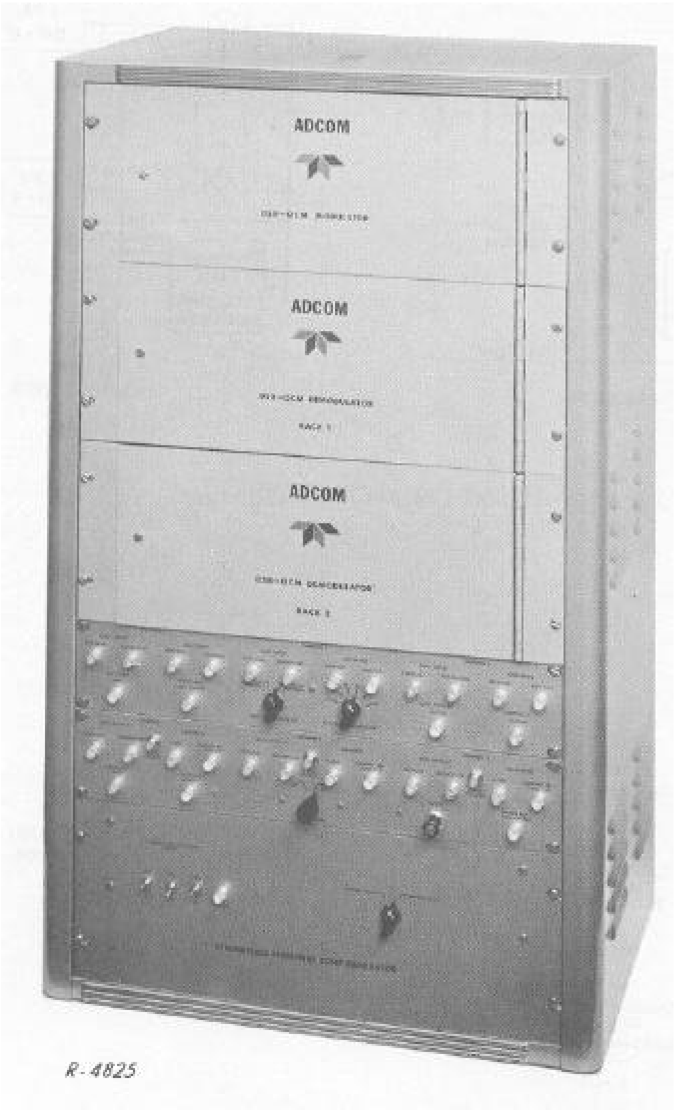

Fig. 3 DSB-QCM Test Modem

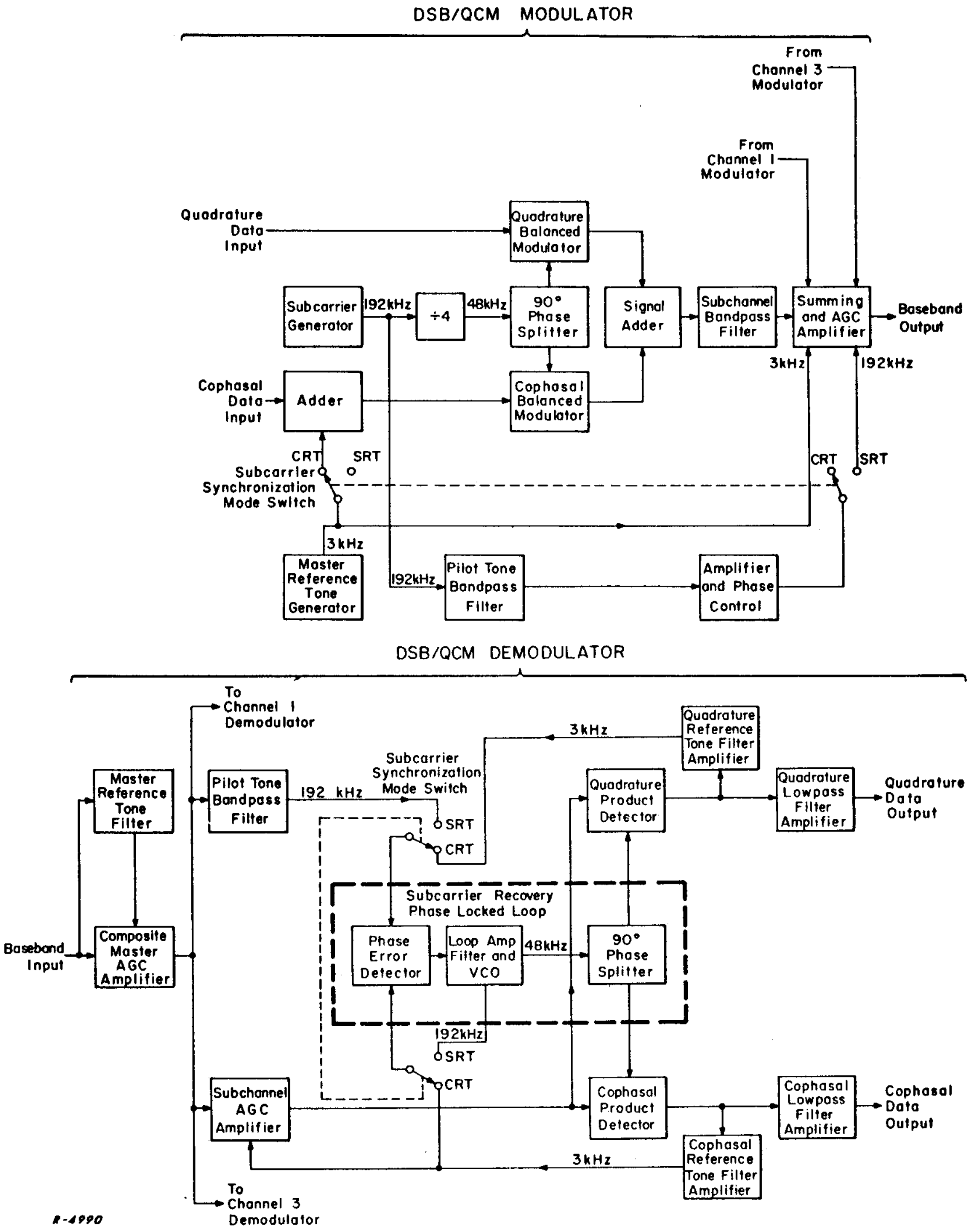

Fig.4 Block Diagram of DSB-QCM Test Modem (One Channel)

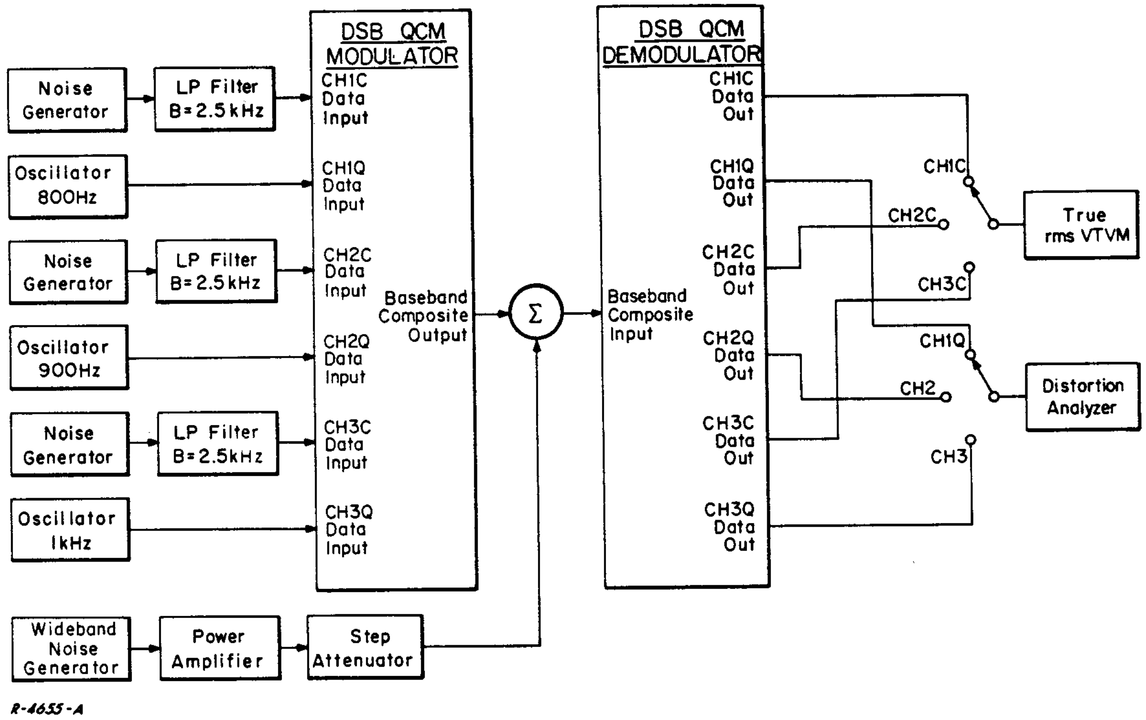

Fig. 5 Block Diagram of DSB-QCM Performance Test Set-Up

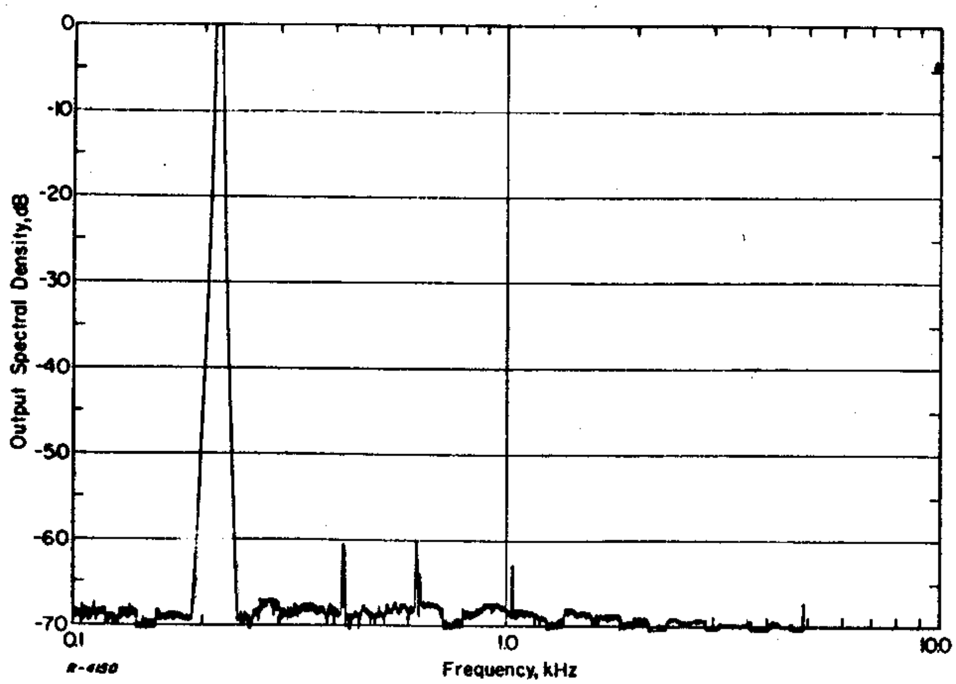

Fig. 6 DSB -QCM Spectral Density Measurements of Crosstalk, without AGC and without Channel Bandpass Filtering

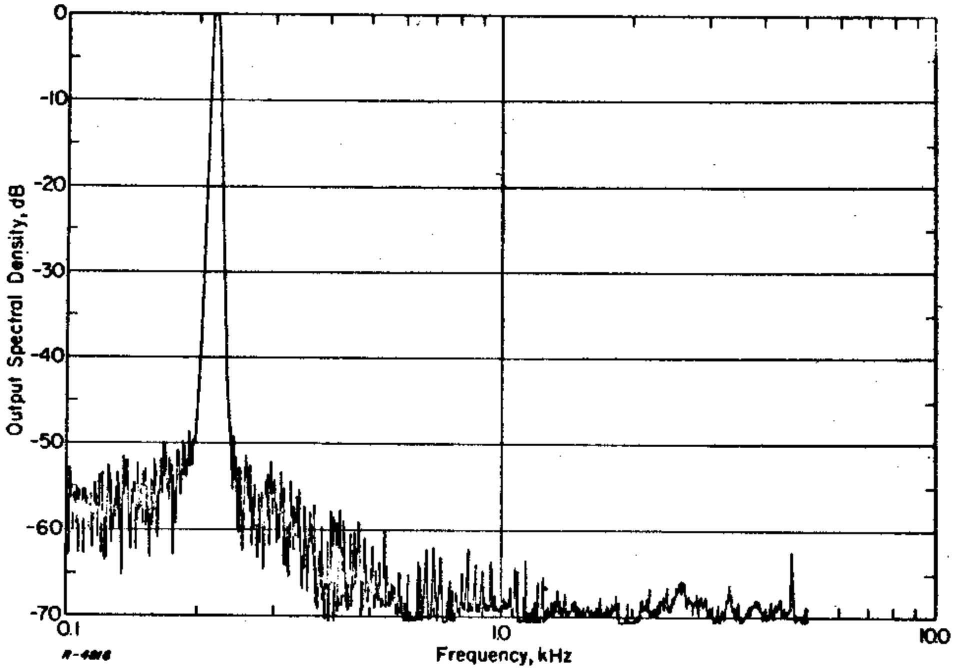

Fig - 7 DSB -QCM Spectral Density Measurements of Crosstalk, with AGC and Channel Bandpass Filtering

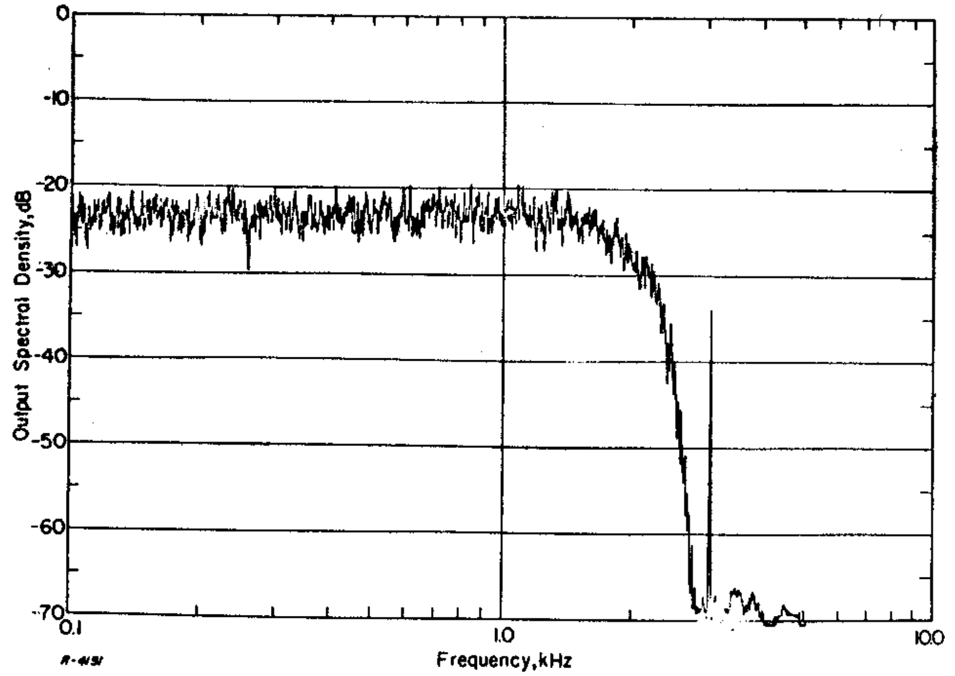

Fig. 8 DSB-QCM Spectral Density Measurements of Crosstalk, Cophasal Noise-Loaded Channel

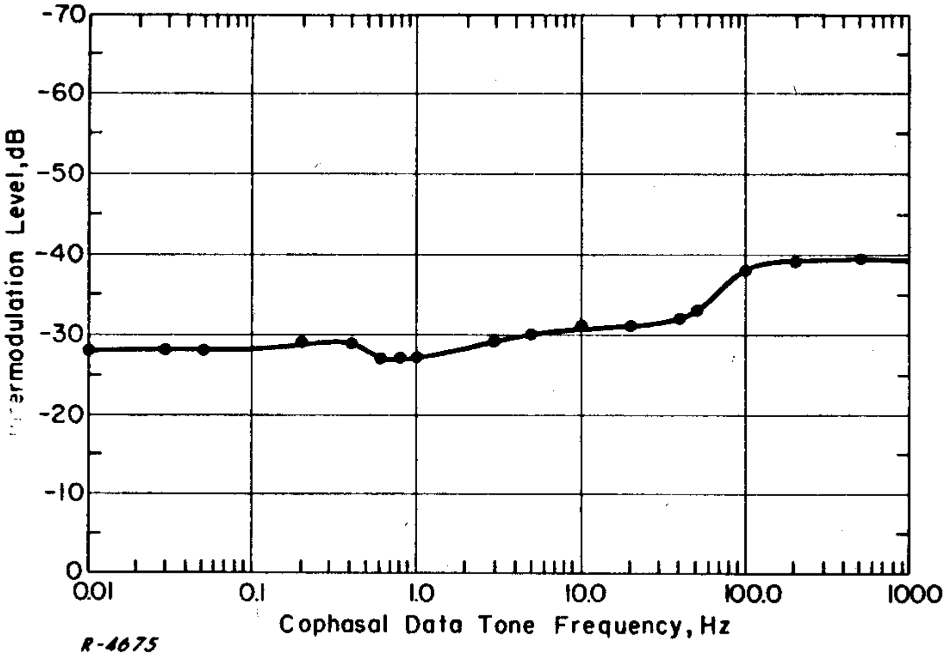

Fig. 9 Low Frequency Intermodulation Performance of a DSB-QCM Channel

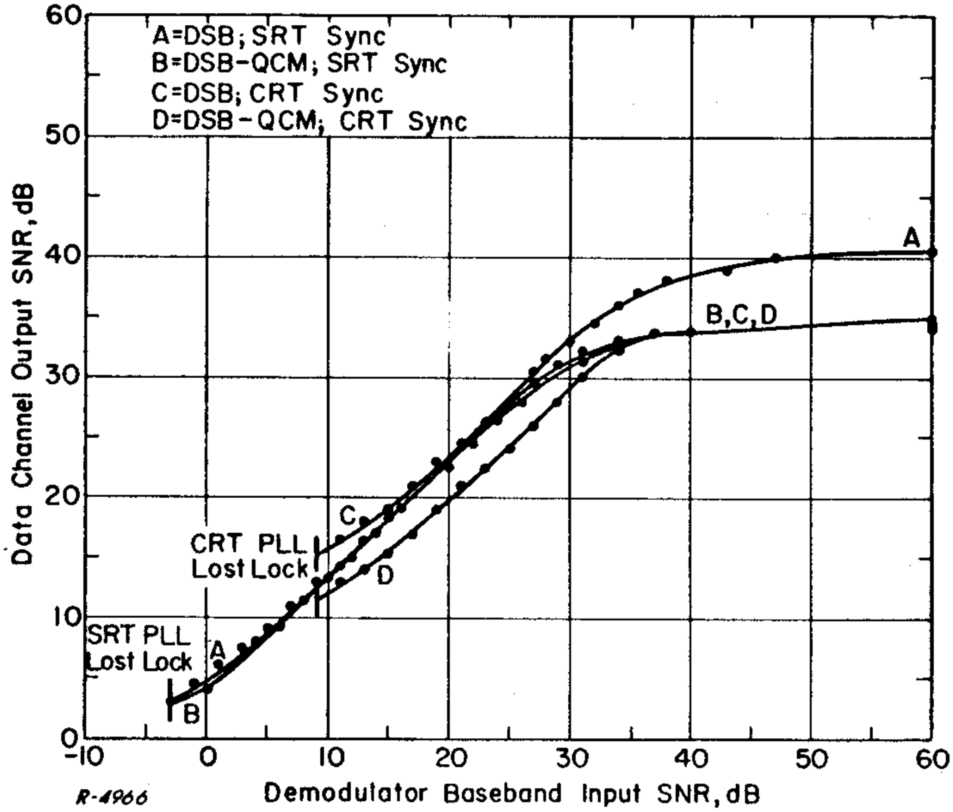

Fig. 10 Baseband Noise Performance of DSB-QCM System: Center Channel Monitored; Adjacent Outboard Channel Subcarrier Spacing 8 kHz

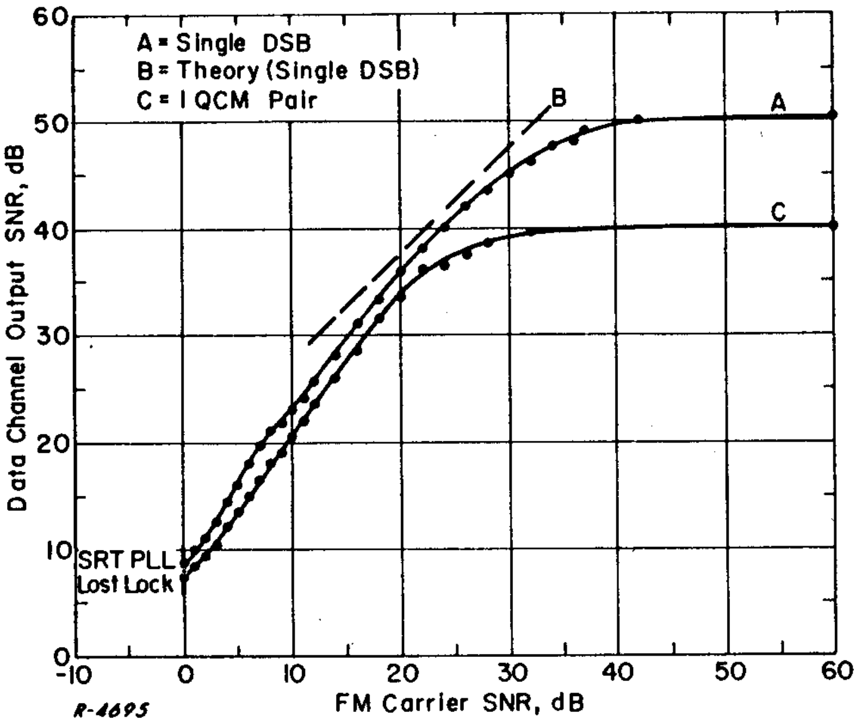

Fig. 11 Noise Performance of DSB-QCM/FM System, SRT Sync Mode, without Composite Baseband AGC

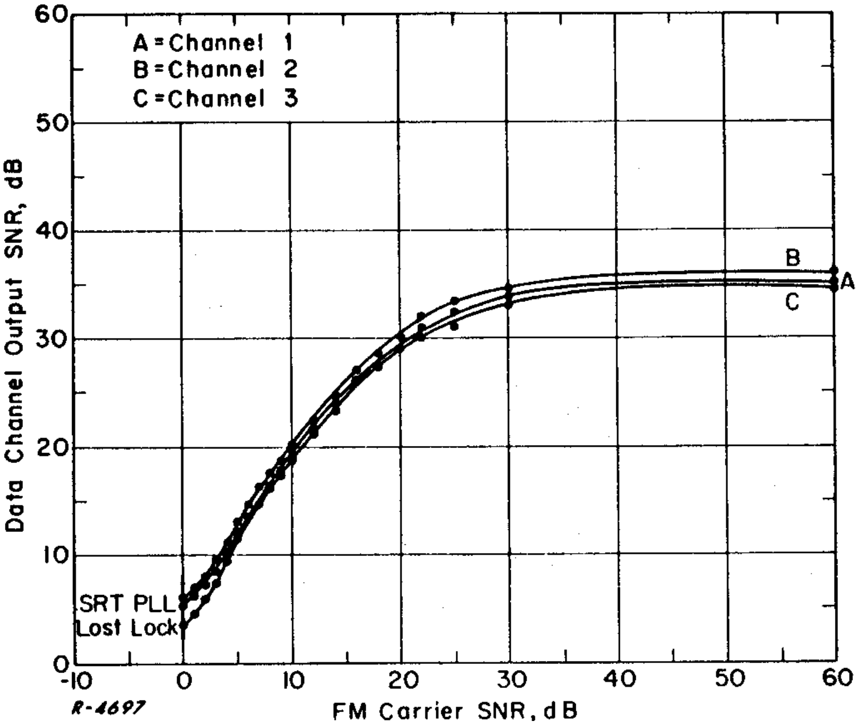

Fig. 12 Noise Performance of Three Channel DSB-QCM/FM System, SRT Sync Mode

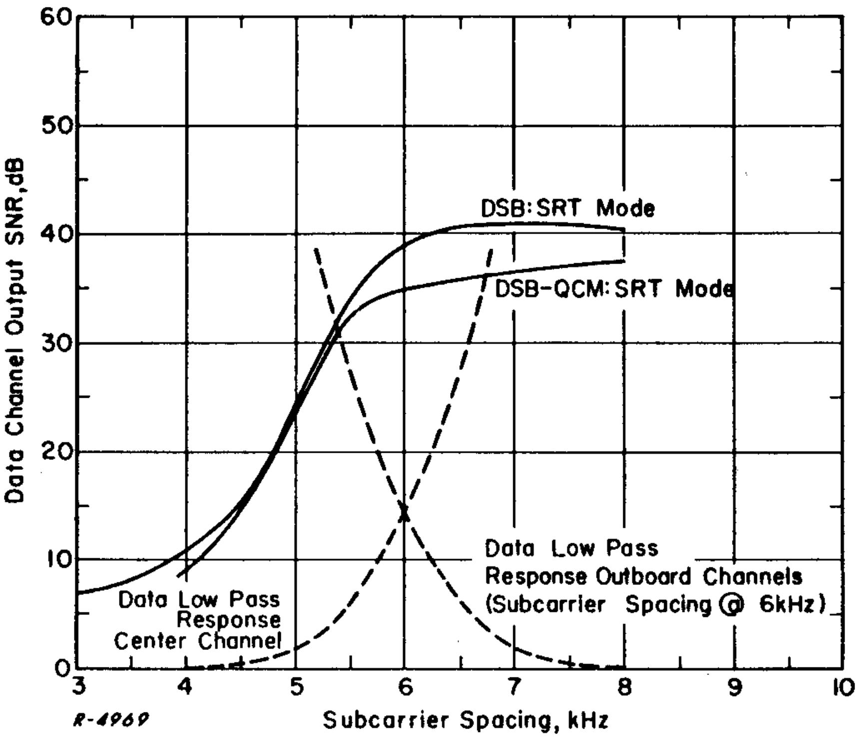

Fig. 13 Three Channel Guardspace Measurements, SRT Sync Mode

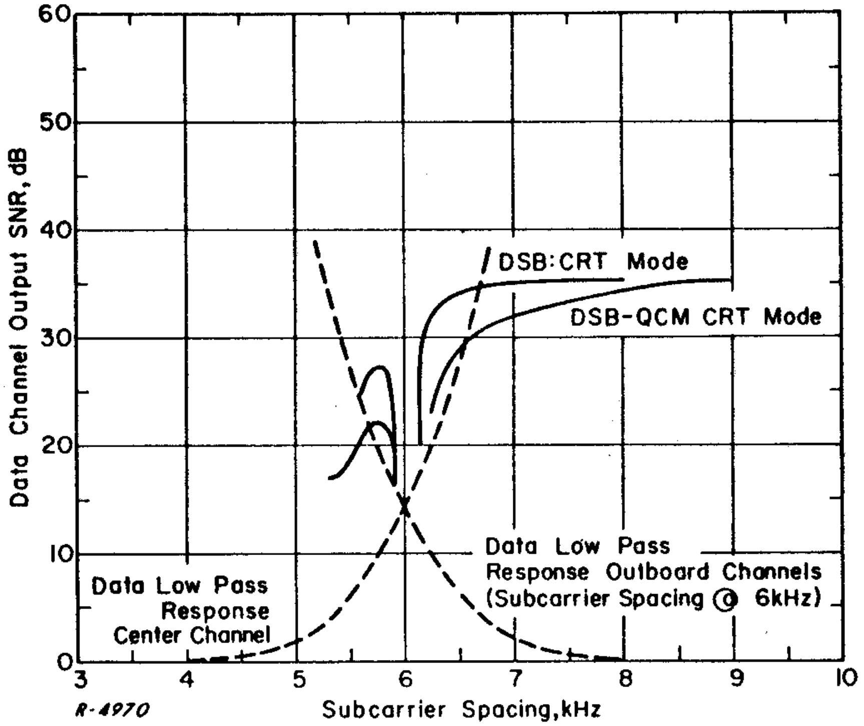

Fig. 14 Three Channel Guardspace Measurements, CRT Sync Mode