AN EXPERIMENTAL EVALUATION OF PAM-NRZ/FM

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Summary The results of a hardware evaluation of PAM-NRZ/FM are presented along with a description of the conditions under which the data were taken. State-of-the-art commutators, transmitters and receivers procured from commercial sources were utilized in the evaluation tests. The principal characteristics of PAM-NRZ/FM considered were data channel response, performance at low signal-to-noise ratios compared to equivalent FM/FM and PCM/FM systems, linearity, crosstalk, overmodulation, transmission noise, data resolution, decommutator synchronization and a comparison of performance at commutation rates of 25,000, 100,000 and 250,000 samples per second. The test data indicates that PAM-NRZ/FM is capable of 2 to 5 percent data transmission accuracy and that performance at low RF levels is comparable to that of FM/FM or PCMJFM under the test conditions specified.

Introduction Although PAM/FM standards have appeared in the Inter-Range Instrumentation Group (IRIG) Telemetry Standards Document 106 for many years, implementation of PAM/FM has for the most part been neglected. A first look at the characteristics of PAM/FM indicates that the data accuracy should fall within 2 to 5 percent, the flexibility of data channel programming by super and sub-commutation is identical to that of PCM and the maximum data sampling rate for a given RF transmission bandwidth may even exceed that of an equivalent 2 percent PCM system. PCM is unquestionably superior and essential for high accuracy data. However, if the maximum accuracy required is in the range of 2 to 5 percent and the data to be transmitted are in analog form, then PAM/FM offers a degree of simplicity, efficiency and economy in the airborne system that is not attainable in PCM since an analog-to-digital converter-encoder would have to be added to transmit PCM. The primary advantages of PAM/FM over FM/FM are flexibility of adjusting the number and response of data channels and the high data transmission capacity possible with one transmitter. The following sections give the results of an experimental comparison of PAM/FM with FM/FM and PCM/FM within the limitations of IRIG Standards.

System Components Commercial equipment was assembled as shown in Figure 1 to provide individual PAM/FM, FM/FM and PCM/FM systems operating over a common

RF transmission link to assure a realistic comparison of PAM/FM with respect to FM/FM and PCM/FM. Components of the PAM/FM system obtained from commercial sources were 25-cubic-inch commutators, 50-cubic-inch S- and L-band transmitters and RF receivers. An experimental commutator for rates higher than 100,000 ch/sec and the PAM decommutator were designed and constructed in the laboratory. No external noise generators, signal modifiers or synthetic test conditions were introduced into the system from the "Analog Data Input" of Figure 1 to the chart recorder. When exploring maximum range or low signal conditions, the transmitted signal was attenuated until receiver noise became a limiting factor.

The transmitting equipment was located in a screen room separate from the receiving and demultiplexing systems. Receivers, decommutators, subcarrier discriminators, tape recorder, chart recorder and supporting equipment were rack mounted in the form of a general-purpose ground station and the various components were interconnected as required at the ground station patch panel.

System Equivalency The validity of comparing PAM/FM performance directly with that of FM/FM and PCM/FM is dependent on equivalent data transfer capability in both quantity and quality in each of the systems under test. The conditions for a given test were pre-set individually in each type of system. The final chart recordings of comparison data were made sequentially by mechanically switching the transmitter input (S1 in Figure 1) from one modulation source to another.

Specifications for FM/FM, PAM/FM and PCM/FM systems considered to be equivalent for the purpose of the evaluation tests are given in Table I.

FM/FM A commonly used form of the FM/FM system was selected as the basis for establishing equivalent PAM and PCM systems. The FM subcarriers selected were IRIG channels 1 through 13, A, C and E with channel E commutated to provide additional low-frequency data channels. The maximum data response in FM/FM was therefore 1200 cps in channel C.

The relative subcarrier oscillator amplitudes in the system under test were adjusted in accordance with standard procedures to equalize susceptibility to noise in the subcarrier discriminators. The subcarriers utilized in the tests were IRIG channels 7, 8, 9, 10, 11, A, C and E omitting channels 1, 2, 3, 4, 5, 6, 12 and 13 listed in Table 1. It can be safely assumed that omitting the lower frequency subcarriers offered no disadvantage to FM/FM performance at low signal-to-noise ratios. A slight advantage would be expected since the RF deviation ratio for the channels included was necessarily higher to compensate for the channels omitted. No pre-modulation filter was required in FM/FM. The receiver video filter cutoff was 100 KC and the discriminator bandpass and lowpass filters (for IRIG channel C) were 40 KC±15 percent and 1.2 KC, respectively.

PAM/FM A PAM-NRZ commutation rate of 25,000 samples per second with 64 channels per frame and appropriate super commutation as shown in Table I was selected to provide a sufficient number of data channels with the required response to compare favorably with the FM/FM system specified. The PAM/FM pre-modulation and receiver video filters were dc to 50 KC, gaussian. The cutoff frequency was four times the 12.5 KC fundamental of 25,000 PAM-NRZ channels per second.

Automatic calibration correction in the decommutator was utilized in all PAM/FM data presented. Offset and sensitivity correction was provided by the center zero and full scale reference levels of the NRZ frame pulse.

PCM/FM A comparable PCM format was readily obtained by substituting six-bit PCM words for PAM channels. Points of similarity between PAM and PCM were the commutation rate, 25,000 samples per second; 64 PAM channels and PCM words per frame; 5 PAM channels and PCM word spaces (30 bits) for frame synchronization; a super-commutated data channel of 8 samples per frame in each system for comparison test data; PAM data accuracy nominally 2 percent and 6-bit resolution in PCM. The PCM pre-modulation and receiver video filters were increased to 100 KC in order to approach optimum video bandwidth. The video cutoff frequency was 0.67 of the 150,000/second bit rate,

RF Spectrums Figures 2, 3 and 4 show a comparison of the RF spectrums of the signals under test. The analyzer settings were: Spectrum Width 100 KC/cm, Vertical Log Scale 0 to -60 db, IF Bandwidth 3 KC. The unmodulated carrier amplitude was set to 0 db.

The criteria selected for RF transmitter deviation were the conditions of equal peak amplitudes of the PAM and PCM square-wave modulation patterns at the transmitter input and equal spectrum widths in PAM/FM and FM/FM over the range of -40 db to -50 db on the spectrum analyzer displays of Figures 2 and 3. The transmitter input was dc-coupled in PAM and PCM and the RF deviation was set to ±125 KC.

The greater spectrum width in PCM, Figure 4, was due to the increased bandwidth required to transmit a six-bit data word in the time period of one PAM channel.

Data Channel Response An inherent difference in the characteristics of frequency-division and time-division multiplexing must be considered in defining equivalent data channel response in FM/FM and PAM/FM. Low-pass output filters in the subcarrier discriminators were selected in accordance with IRIG standards for a subcarrier deviation ratio of 5. The data channel response in FM/FM may be defined in terms of the low-pass output filter characteristics. The use of low-pass output, filters in PAM and

PCM was optional. PAM outputs are normally derived from digital-to-analog converters or analog sample-and-hold devices in which the output is stepped to the exact data level of the commutated input at the time each data sample is taken and between samples, the output remains static at the previously sampled level. There is no inherent constraint in decommutation to prevent a full-scale data level shift in one sampling period within the maximum data accuracy of the system.

Figures 5 through 9 show the response characteristics of comparable FM/FM and PAM/FM data channels at the highest data channel response in the FM/FM and PAM/FM systems specified. IRIG subcarrier channel C is compared with a PAM channel super-commutated every eighth segment in the frame. The PAM data sampling rate was therefore 25,000/8 or 3125 samples per second. The response to transients and complex wave forms is compared in Figures 5, 6 and 7. The upper traces show a square-wave input of 500 cps at the “Analog Data Input” of Figure 1. The lower traces of Figures 5 and 6 show the IRIG Band C subcarrier discriminator output with 1200 cps linear phase and constant amplitude output filters respectively. The lower trade of Figure 7 shows the unfiltered output of the PAM decommutator.

The horizontal overlap of square-wave transitions in the lower trace of Figure 7 represents the maximum variable phase delay of 320 ps and is equal to the time between samples at this sampling rate. It may be observed that the PAM data level shift is completed to the final data amplitude well within the time of a full-scale transition in the 1200 cps discriminator filters. A low-pass filter in the PAM output was found to be detrimental in some cases to high frequency data response and amplitude accuracy. One possible use of an output filter in PAM is shown in Figure 9 where the output data is a continuous sine wave at the upper frequency limit of the PAM channel response. Under this condition, an output filter would be useful in restoring the sine wave form for visual frequency analysis. Figure 8 shows a full-scale modulated I KC sine wave at the output of the IRIG channel C discriminator. The identical I KC signal in the PAM channel having a 1.2 KC Butterworth output filter is shown in Figure 9. The PAM data sampling rate of 3125 per second provided 3.125 samples per cycle at 1 KC.

Comparison Tests at Low Signal-to-Noise Ratios Figures 10 and 11 show the relative performance of PAM/FM when compared with FM/FM and PCM/FM respectively under low signal-to-noise conditions. The data modulation was a 50 cps triangular wave form adjusted at the “Analog Data Input” of Figure 1 to full scale data modulation in the three systems. The receiver IF bandwidth was 300 KC, chart recorder galvanometer response 5 KC, and chart speed 16" per second. PAM and PCM decommutator outputs were unfiltered. The FM/FM and PAM/FM data channels compared in Figure 10 are the same channels described and compared for equal response in Figures 5 through 9. The PCM data sampling rate in Figure 11 was identical to that of PAM.

The PAM format used in the signal-to-noise tests is shown in Figure 12. The test results indicate that the performance of PAM/FM compares favorably with FM/FM and PCM/FM at low signal-to-noise ratios under the operating conditions specified. Detectable noise appeared in the PAM and PCM data at 0 db reference level in Figures 10 and 11, however, the effects of noise in the FM/FM data were greater than in PAM at -6 db in Figure 10. PAM data was intermittent at -8 db due to loss of frame synchronization over relatively long periods of time. Figure 13 shows the degraded quality of the receiver output signal at the threshold of PAM synchronization (-8 db in Figures 10 and 11).

Effects of Data Modulation on PAM-NRZ Synchronization The number of channel synchronization pulses derived from PAM-NRZ signals in the decommutator is dependent on the data levels in adjacent channels being unequal by at least 20 percent of full scale. False frame signals are introduced into the system if five consecutive data channels assume the approximate levels of the five true frame pulse segments. The following tests were designed to compare data quality under ideal and adverse channel modulation patterns with regard to channel and frame synchronization. The tests were performed at a low signal-to-noise ratio where loss of synchronization would most likely occur.

Figure 14 is a reference of data quality at a high signal-to-noise ratio for the test data presented in Figures 15, 16 and 17. The commutator pattern in Figure 15 shows a super-commutated format of 10 modulated channels in a 60-channel frame. Data amplitudes in the remaining fixed channels provided the maximum possible number of 58-channel transitions per frame during part of a 5 cps data modulation period. The number of transitions varied from 58 to 39 per frame as the modulation level passed from +20 percent through center zero to -20 percent. The decommutator output data at a low signal-to-noise ratio are shown in the chart recording of Figure 15.

Figure 16 shows a commutation pattern in which the number of transitions varied from 22 to the absolute minimum of 3 per frame as the modulation level passed through center zero. The chart recording of Figure 16 may be compared with that of Figure 15 for data quality at the same signal-to-noise ratio.

A false frame synchronization pulse was introduced in the center of some of the frames in the commutation pattern of Figure 17. The false frame occurred over 25 percent of the modulation cycle as the data approached maximum positive amplitude. The chart recording of Figure 17 may also be compared with the recording in Figure 15 at the same signal-to-noise ratio.

The test results in Figures 15, 16 and 17 indicate that it is possible to maintain adequate synchronization with minimum loss of data under adverse channel modulation patterns combined with low signal-to-noise ratios.

Data Quality, Linearity, Resolution and Crosstalk A comparison of the effects of noise in high and low response PAM/FM data channels is shown in Figure 18 at a low signal-to-noise ratio. The modulation frequency was 5 cps in both channels. The data were sampled once per frame in the upper trace of Figure 18 and ten times per frame, super-commutated in the lower trace. The decomutator outputs were unfiltered. The characteristics of noise in high and low response PAM/FM data channels were found to be similar to those of equivalent high and low subcarrier channels in a properly adjusted FM/FM system.

PAM/FM system linearity from the commutator input to the chart recorder is shown in the recordings of Figure 19. An adjustable precision dc voltage source was connected to the “Analog Data Input” of Figure 1. The linearity shown is typical of that found with several types and combinations of commutators, transmitters and receivers. The principal source of nonlinearity was traced to the receiver and the system non-linearity varied from 0.5 percent to 1.5 percent with four types of commercially available receivers tested in the system. Figure 19 also shows typical background noise and data resolution characteristics that may be expected with a transmitter deviation of ±125 KC in the 2200-2290 MC transmission band. Incidental FM in the transmitter and receiver appeared in the form of background noise in the decommutated output. The effect was maximum in Figure 19 where the RF carrier was in the highest frequency transmission band (2200-2290 MC) and the deviation was the minimum considered suitable for PAM/FM. Measured incidental FM in the transmitter was ±3 KC. The peak noise level in Figure 19 was approximately I percent of full scale data.

Data resolution may be estimated by observing the 1, 2 and 3 percent data level steps identified in Figure 19. A I percent change in data level was easily detectable.

System crosstalk and overmodulation test data and photographs of the commutation pattern utilized are shown in Figure 20. A 60-channel per frame commutator with every sixth channel modulated was recorded in the upper data trace at a full scale amplitude of 2 cm. The lower trace shows data in super-commutated segments immediately following each modulated segment in the commutation pattern with full scale amplitude set to 10 cm on the chart. Both data channels were modulated by the same source at the left of Figure 20 to establish full scale calibration on the chart. The commutator input to the lower trace channel was then switched to a fixed dc level. Later in the recording, the upper trace channel was overmodulated at the commutator input. This was considered to be the most severe condition for channel crosstalk that would be encountered in practice.

If a significant amount of crosstalk has been introduced within the system, the waveform in the top trace would have been detectable in the lower unmodulated trace.

Comparison of PAM-NRZ/FM Performance at Commutation Rates of 25,000, 100,000 and 250,000 Samples Per Second The data transmission capacity of PAM/FM may be increased by raising the commutation rate and scaling up transmitter deviation, receiver IF bandwidth and video filters within the limitations of the system components. The system parameters listed in Table II refer to the operating characteristics under which the data in Figure 21 were taken.

TABLE II
System Parameters for the Test Data in Figure 21

SYSTEM PARAMETER	COMMUTATION RATE, Samples/Sec 25,000	100,000	250,000
Pre-Modulation Filter (Gaussian)	50 KC	200 KC	800 KC
RF Deviation	±125 KC	±200 KC	±600 KC
Receiver IF Bandwidth	300 KC	500 KC	1.5 MC
Receiver Video Filter (Gaussian)	50 KC	200 KC	750 KC

The commutation format remained fixed during the tests and the data channel recorded was super-commutated at ten channels per frame in a 60-channel frame. Referring to Figure 21, the top oscilloscope trace at each commutation rate shows an expanded view of the receiver output signal. Directly below is a dual trace presentation of the receiver output signal and the decommutated data output with the baseline synchronized to the data frequency. The nominal high frequency limit of the data channel was 1 KC at the commutation rate of 25,000 samples per second. Increasing the commutation rate from 25,000 to 100,000 and 250,000 samples per second increased the data channel response in direct proportion to 4 KC and 10 KC respectively. The decommutated sine wave outputs of 1 KC, 4 KC and 10 KC are shown in the lower portion of the dual trace photograph for each commutation rate. Approximately four samples per modulation cycle were provided at the decommutator output. The waveform was restored by a Butterworth filter having a cutoff frequency of 1.2 times the modulation frequency. The sinewave data amplitude was subject to interpolation error under these conditions. Information relating samples per modulation cycle, filter characteristics and interpolation error is available in Reference 1.

The chart recordings in the lower portion of Figure 21 show decommutated data at both high and low signal-to-noise ratios. The modulation signal was 50 cps triangular and unfiltered at the decommutator output. The system parameters in Table II were arbitrarily chosen to simulate possible operating conditions in practice.

Conclusions should not be drawn from Figure 21 relative to performance at low signal-to-noise ratios without first considering the conditions given in Table II. It may be noted for example that the 25,000 samples per second commutation rate was given an advantage in RF deviation ratio. The results of this test show feasibility of PAM-NRZ/FM data transmission at commutation rates up to 250,000 samples per second. The video response of the transmission link, however, was marginal at the highest rate as may be noted by comparing the square wave response in the RF receiver output oscilloscope traces at the top of Figure 21.

Conclusions An analysis of the test data indicates that a PAM-NRZ/FM system is capable of 2 percent data transmission accuracy and the performance at low signal-to-noise ratios compares favorably with FM/FM and PCM/FM under the operating conditions described herein. It was noted that the comparative performance of the PAM/FM, FM/FM and PCM/FM systems utilizing actual airborne and ground station type hardware closely followed the theoretical predictions contained in the Aeronutronic "Telemetry Systems Study", Reference 2.

Automatic calibration correction in the PAM decommutator was found to be highly effective in maintaining data accuracy with receiver detuning and low frequency offset variations in the receiver video output.

Several equipment requirements are of particular interest in selecting components for PAM/FM. DC response is required in the transmission link, therefore, dc coupling or dc restoration must be provided in the transmitter modulator and a dc coupled video amplifier and filter are required in the receiver. PAM/FM linearity is a function of the linearity of the transmitter modulator and the receiver discriminator. The ratio of incidental FM deviation to full scale signal deviation is the major factor affecting transmission noise at high RF signal levels. Video response in the transmission link should provide sufficient rise time with minimum overshoot and amplitude distortion such that the commutator pulse amplitudes approach the final data values at the receiver output within 25 percent of the channel period after channel "on" time. Insufficient rise time or overshoot which continues beyond the first quarter of the channel period may introduce channel crosstalk into the system.

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References

(1) L. W. Gardenhire, “The Use of Digital Data Systems:, Proc. National Telemetering Conference 1963, Art 3-1.

(2) “Telemetry Systems Study-Final Report”, Aeronutronic Publications U-743, 18 Dec 1959.

Table I - Data Capacity Comparison of the Systems Under Test

FM/FM SYSTEM IRIG Subcarrier Bands		PAM-NRZ/FM SYSTEM* 25,000 Channels/Sec 64 Channels/Frame 40 µs - Channel Period			
Channel	Response	Commutator Channel Assignments (64 Total)	Samples Per Data Channel	Time Between Samples	Notes
E	(Commutation 900 Ch/Sec) 28 Data Channels 30 Samples/Sec (Each)	32	391 (Each)	2.56 Msec (Each)	32 Data Channels 391 Samples/Sec (Each)
C**	1.2 KC	8**	3125	320 µsec	Super-commutated, 8 samples/frame
A	660 cps	4	1562	640 µsec	Super-commutated, 4 samples/frame
13	220 cps	2	781	1.28 Msec	Super-commutated, 2 samples/frame
12	160 cps	2	781	1.28 Msec	Super-commutated, 2 samples/frame
11	110 cps	1	391	2.56 Msec	One sample/frame
10	81 cps	1	391	2.56 Msec	One sample/frame
9	59 cps	1	391	2.56 Msec	One sample/frame
8	45 cps	1	391	2.56 Msec	One sample/frame
7	35 cps	1	391	2.56 Msec	One sample/frame
6	25 cps	1	391	2.56 Msec	One sample/frame
5	20 cps	1	391	2.56 Msec	One sample/frame
4	14 cps	1	391	2.56 Msec	One sample/frame
3	11 cps	1	391	2.56 Msec	One sample/frame
2	8 cps	1	391	2.56 Msec	One sample/frame
1	6 cps	1	391	2.56 Msec	One sample/frame
		5	391	2.56 Msec	NRZ Frame Pulse & 3 Level Calib.

* PAM channels were replaced by PCM words for identical PCM data capacity.
** Data channels compared in the evaluation tests

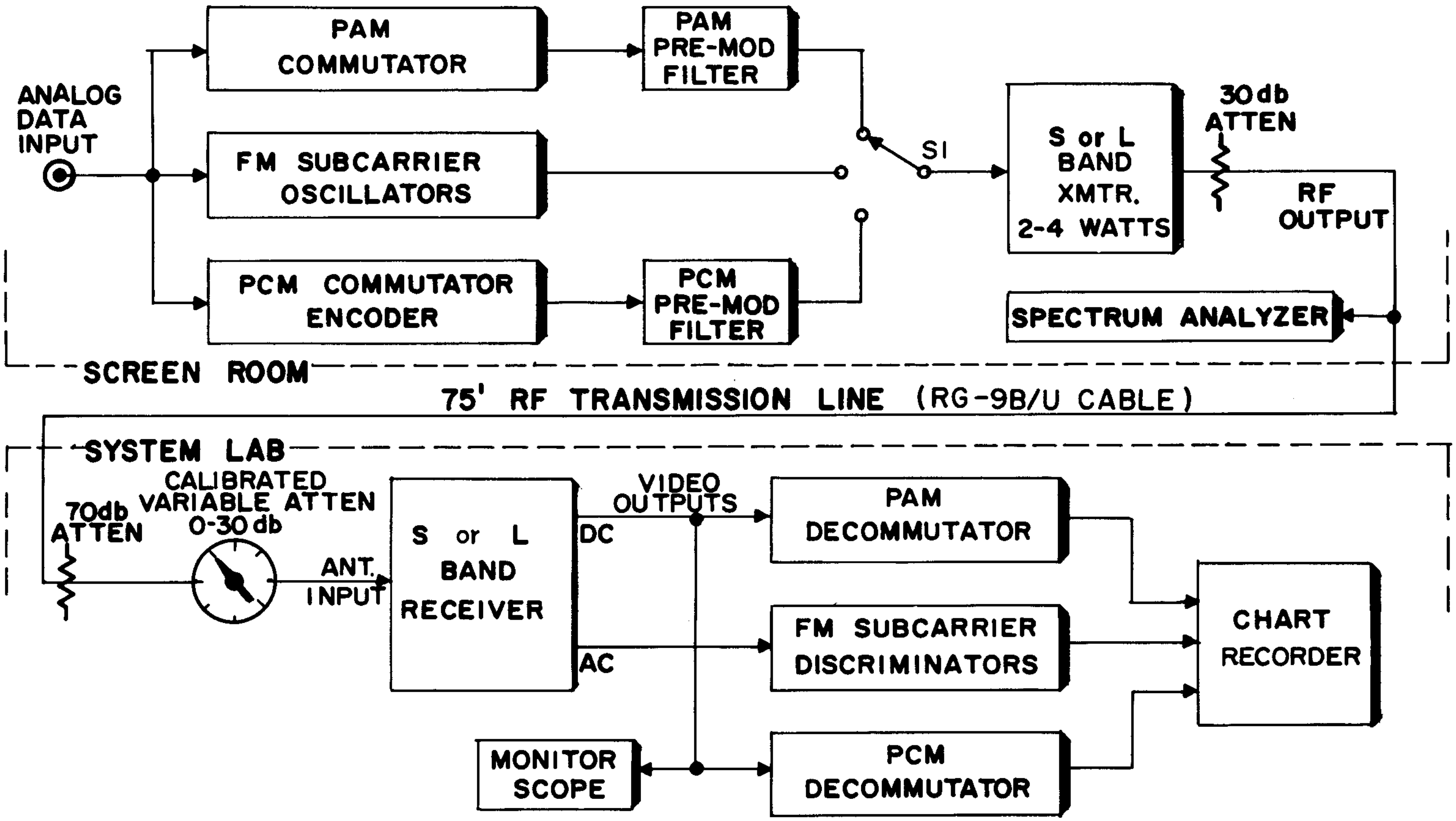

Fig. 1 - Equipment Arrangement for Evaluation Tests

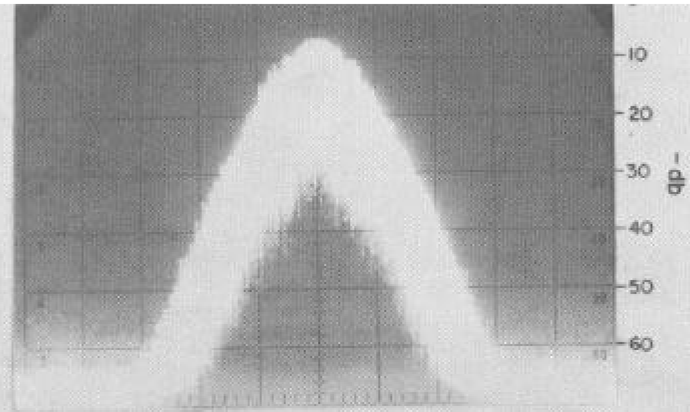

FIGURE 2. FM/FM RF SPECTRUM

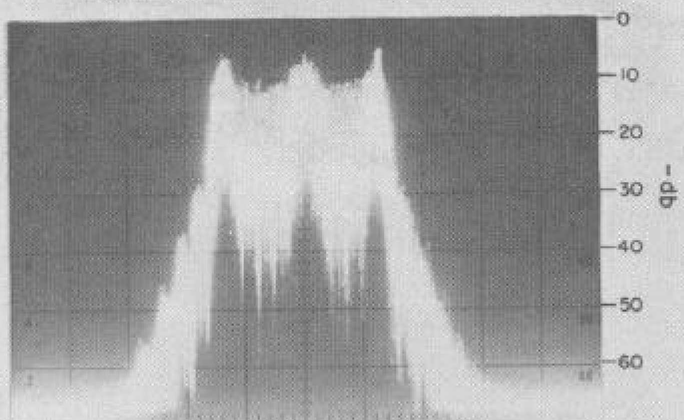

FIGURE 3. PAM RF SPECTRUM

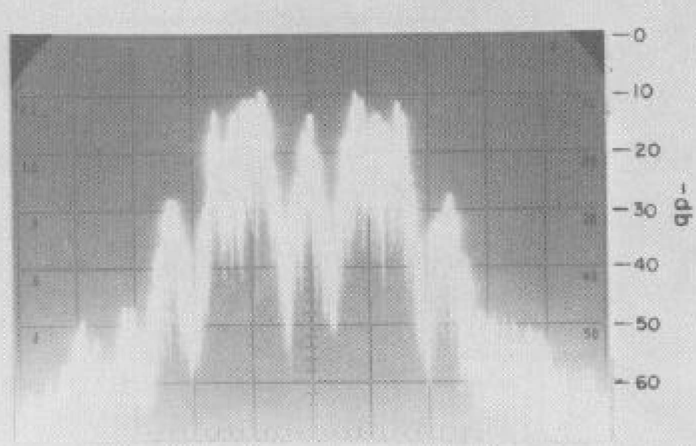

FIGURE 4. PCM RF SPECTRUM

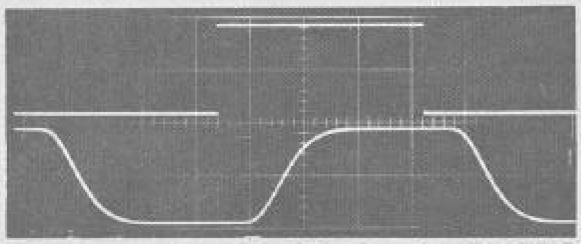

FIGURE 5. FM/FM CHANNEL C RESPONSE
1.2 Kc Linear Phase Filter

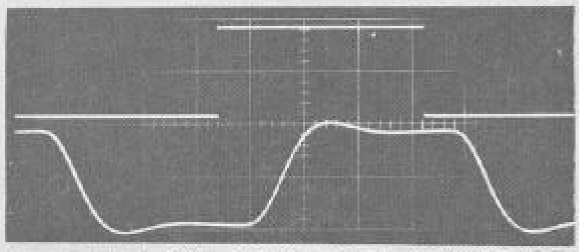

FIGURE 6. FM/FM CHANNEL C RESPONSE
1.2 Kc Constant Amplitude Filter

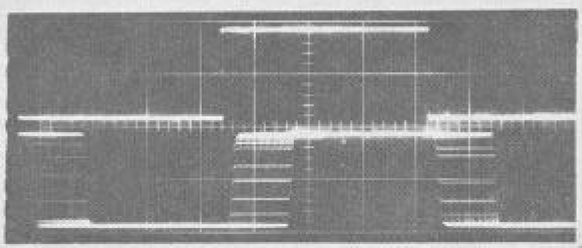

FIGURE 7. PAM/FM RESPONSE 3125 Sample/Sec
No Output Filter

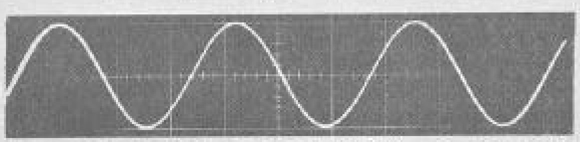

FIGURE 8. FM/FM CHANNEL C RESPONSE
1Kc Sine Wave 1.2 Kc Filter

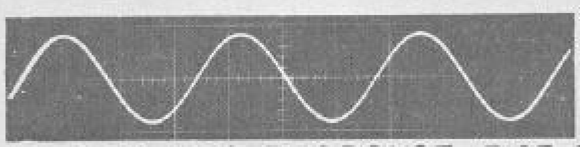

FIGURE 9. PAM/FM RESPONSE 3125 Sample/Sec
1Kc Sine Wave 1.2 Kc Filter

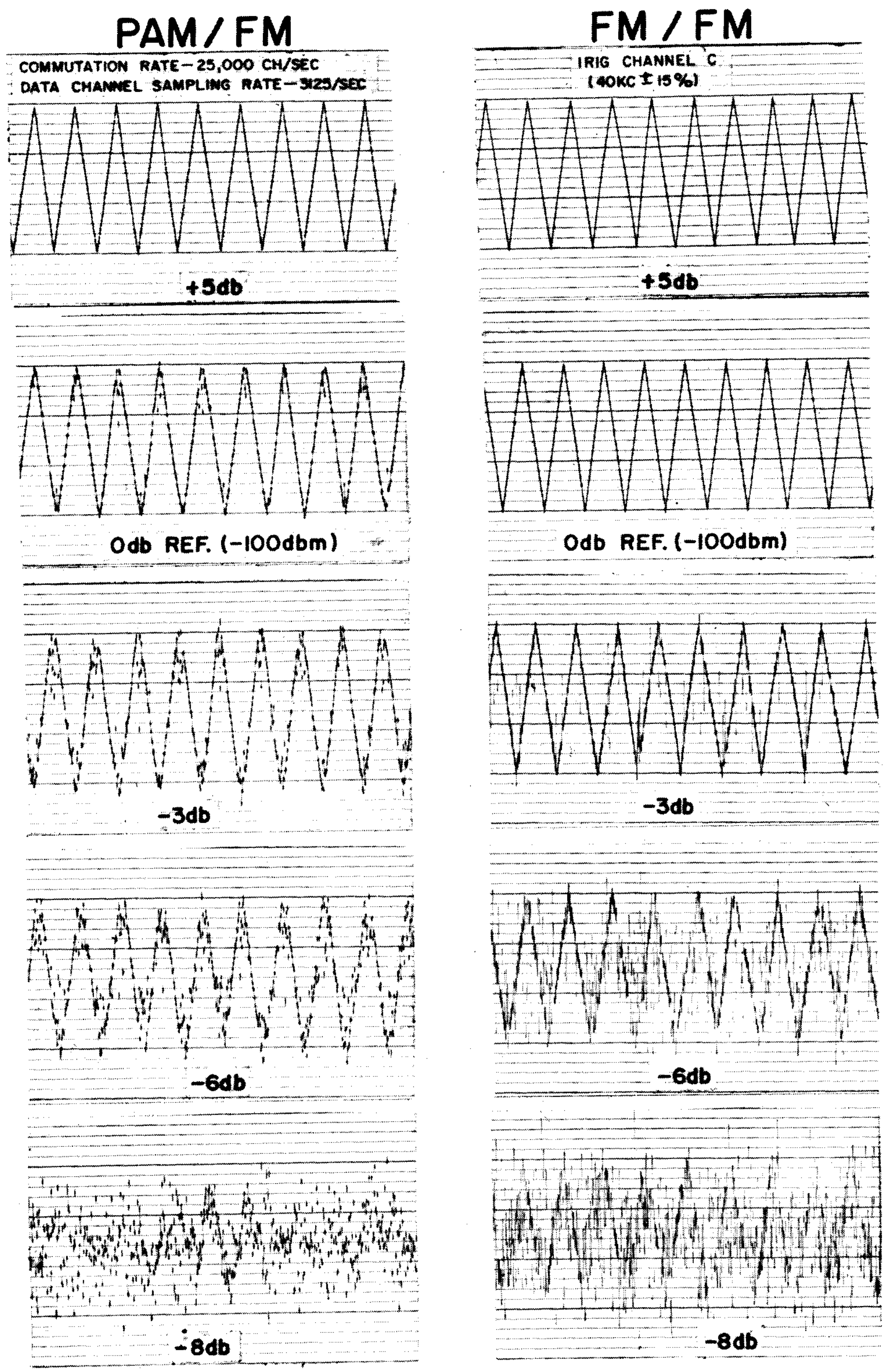

Fig. 10 - PAM/FM - FM/FM Signal-To-Noise Test

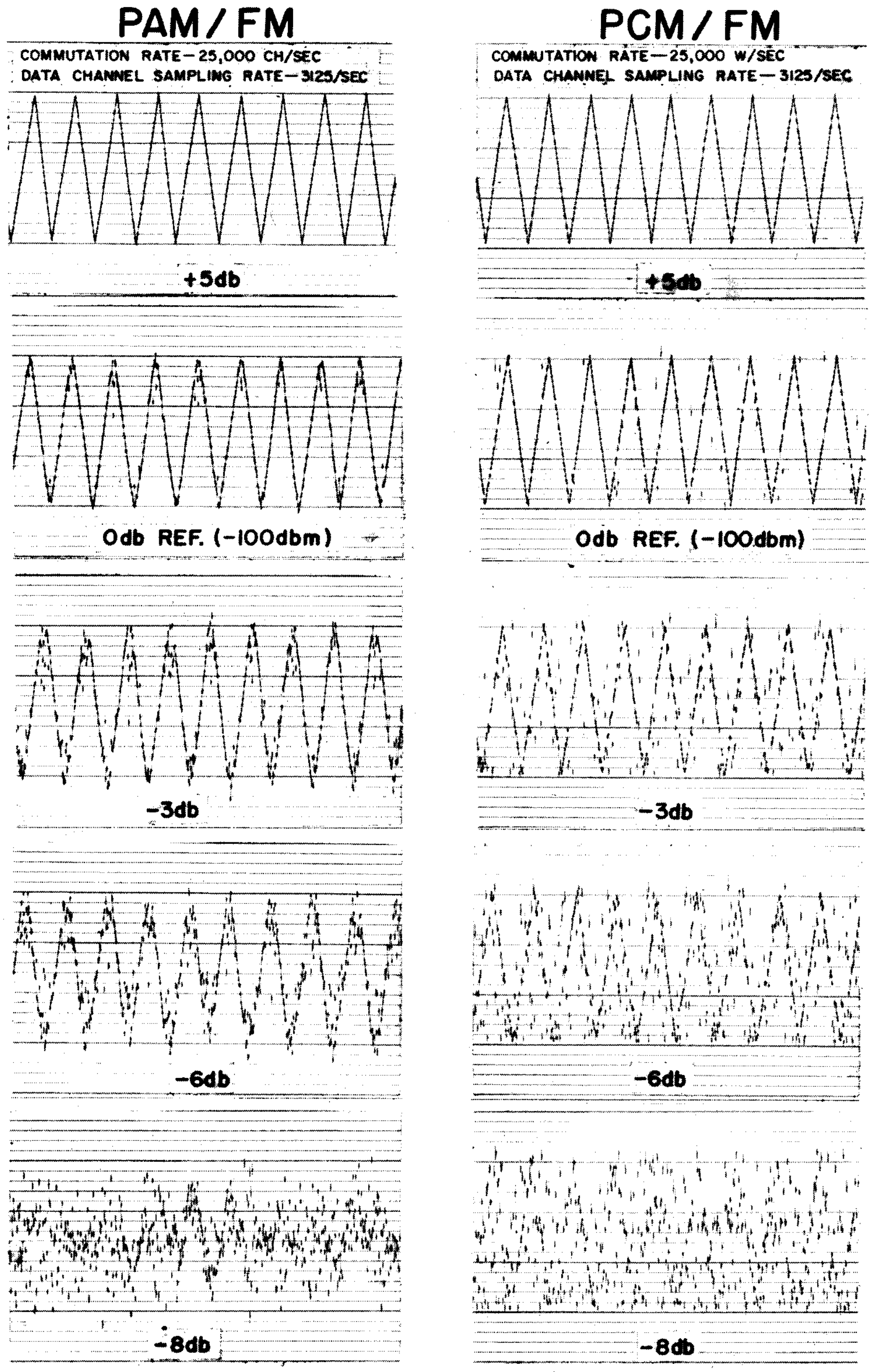

Fig. 11 - PAM/FM - PCM/FM Signal-To-Noise Test

FIGURE 12. PAM-NRZ FORMAT FOR NOISE TESTS OF FIGURES 10 & 11.

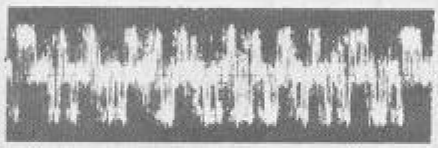

FIGURE 13. PAM-NRZ AT RECEIVER OUTPUT -106dbm (-8db IN FIGS. 10 & 11)

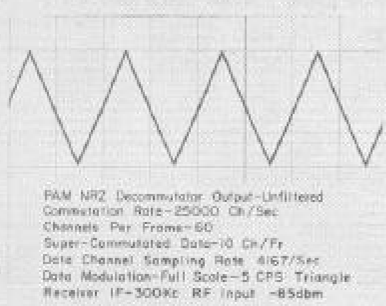

FIGURE 14. DATA QUALITY REFERENCE FOR FIGURES 15, 16, 17 & 18.

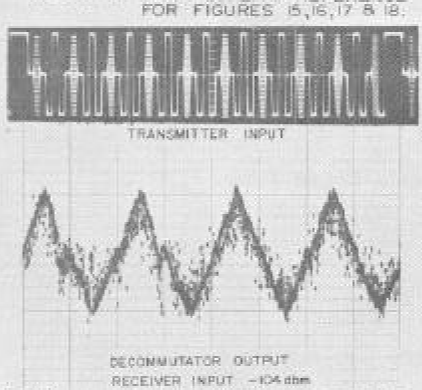

FIGURE 15. MAXIMUM NUMBER OF CHANNEL TRANSITIONS.

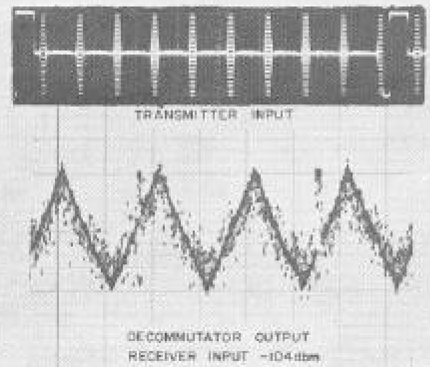

FIGURE 16. MINIMUM NUMBER OF CHANNEL TRANSITIONS.

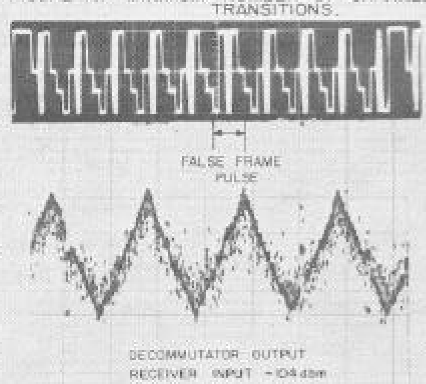

FIGURE 17. INTERMITTENT FALSE FRAME PULSE.

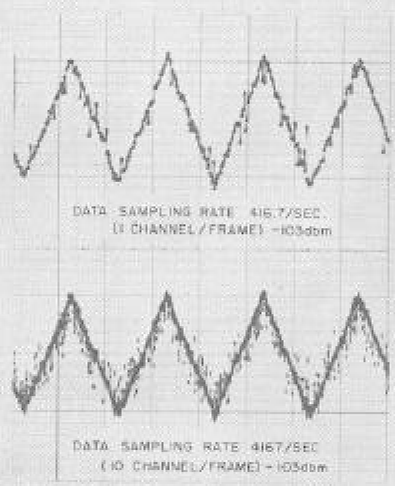

FIGURE 18. HIGH AND LOW DATA CHANNEL SAMPLING RATES.

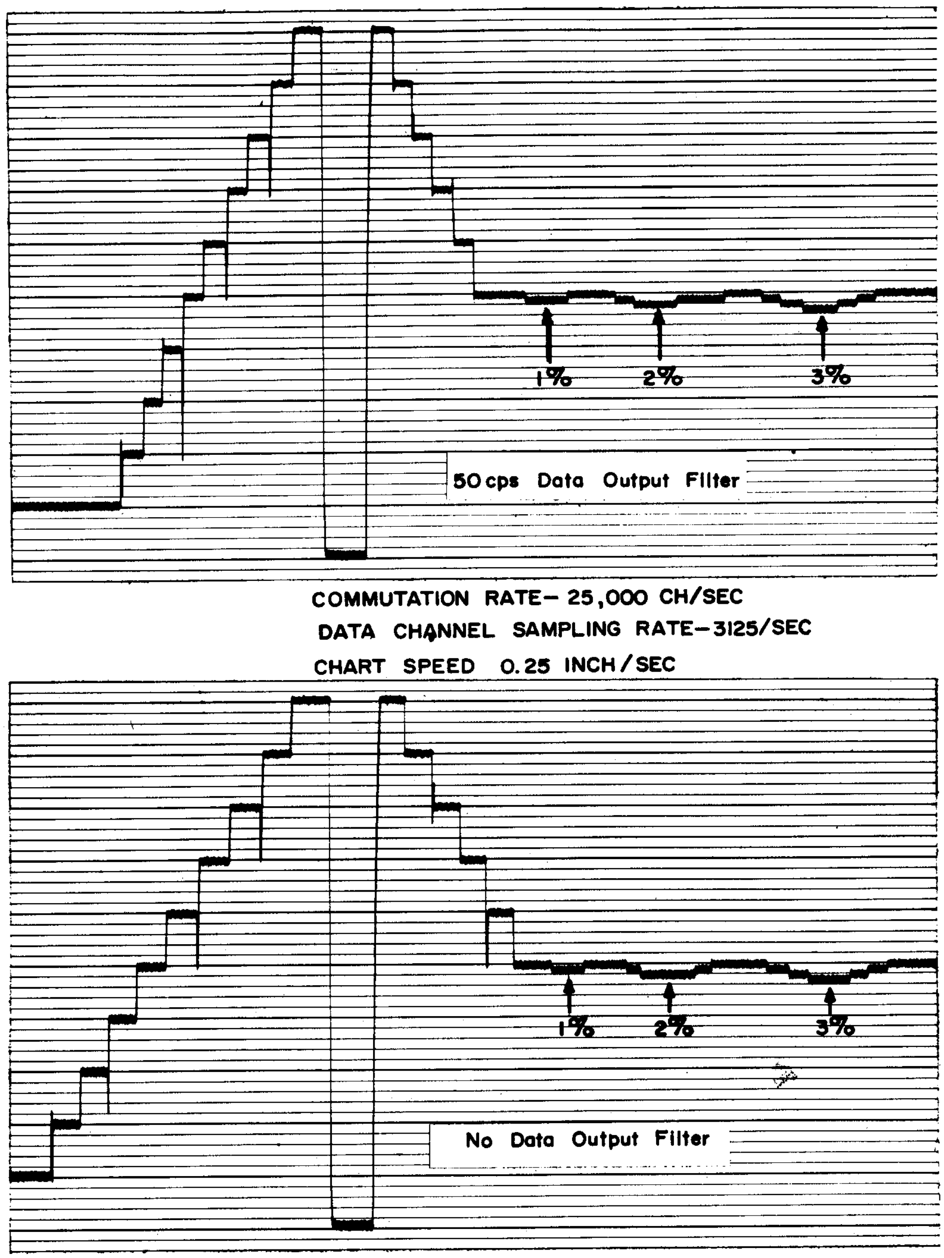

Fig. 19 - PAM-NRZ/FM Linearity and Data Resolution

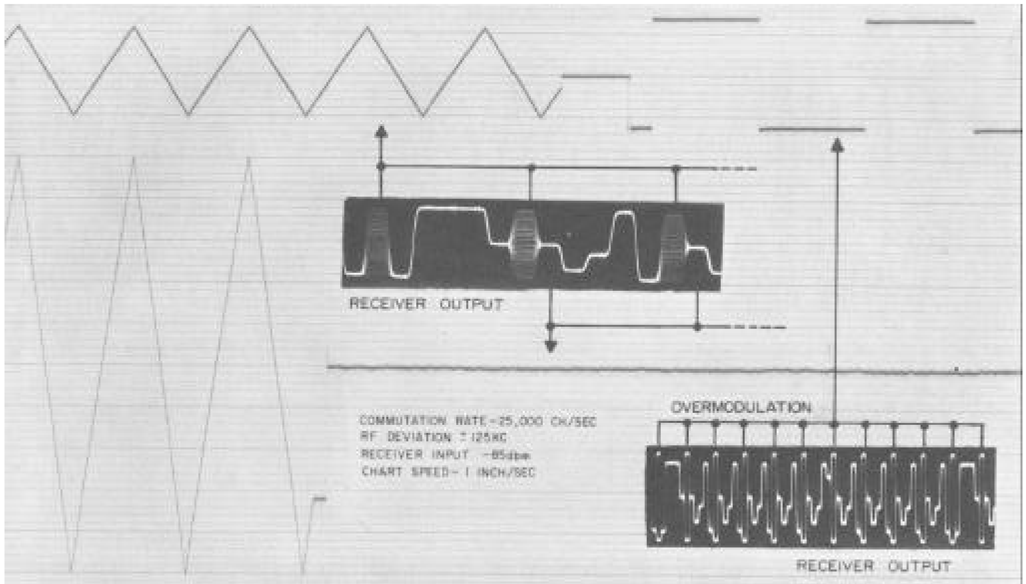

Fig. 20 - PAM-NRZ/FM Crosstalk and Overmodulation

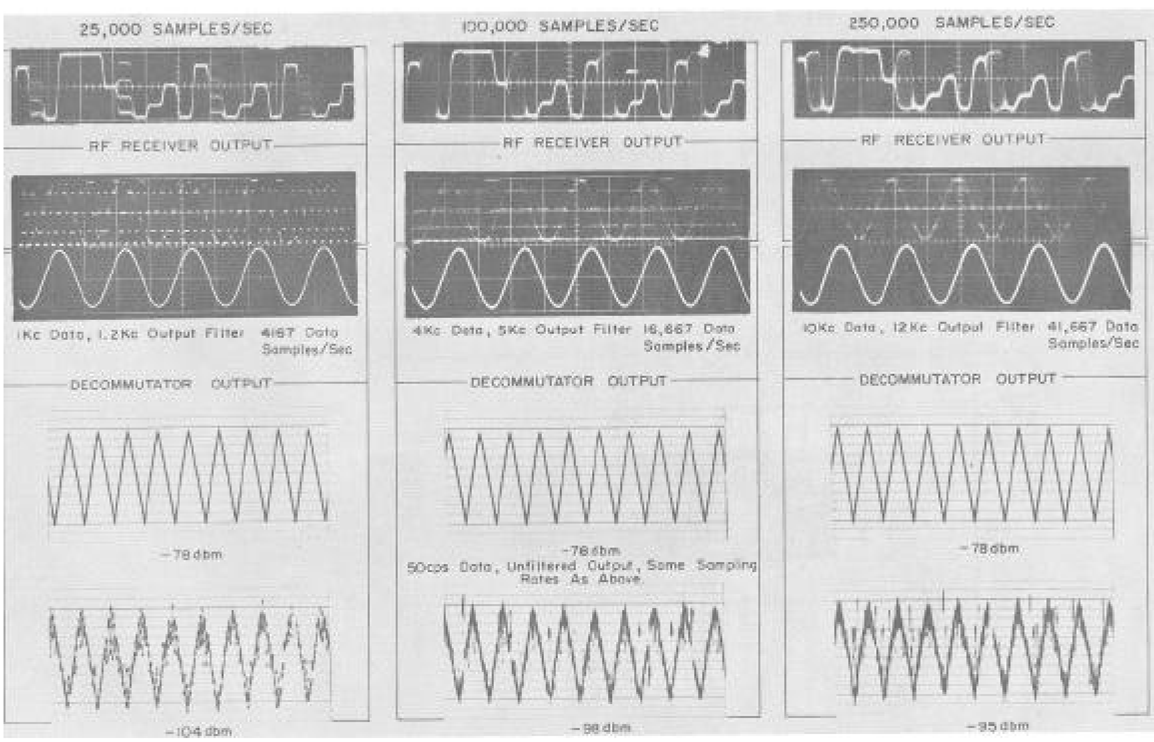

Fig. 21 - Comparison of PAM-NRZ/FM Performance at Commutation Rates of 25,000, 100,000 and 250,000 Samples Per Second