TELEMETRY FM/FM BASEBAND STRUCTURE STUDY

VOLUME I
FINAL REPORT FOR:
WHITE SANDS MISSILE RANGE
NEW MEXICO
CONTRACT DA-29-040-AMC-746 (R)

PREPARED BY:
E. B. CAMPBELL
AND
W. R. HERBERT
14 JUNE 1965

EMR
ELECTRO-MECHANICAL RESEARCH, INC.
SARASOTA, FLORIDA

TELEMETRY FM/FM BASEBAND STRUCTURE STUDY

VOLUME I
FINAL REPORT FOR:
WHITE SANDS MISSILE RANGE
NEW MEXICO
CONTRACT DA-29-040-AMC-746 (R)

PREPARED BY:
E. B. CAMPBELL
AND
W. R. HERBERT
14 JUNE 1965

EMR

ELECTRO-MECHANICAL RESEARCH, INC.
SARASOTA, FLORIDA

FOREWORD

The conclusions and recommendations in this report are based solely on the technical considerations of expanding the standard FM/FM baseband. They are one of many inputs which the Telemetry Working Group of the Inter-Range Instrumentation Group must consider as they contemplate revisions to the published standards. It is anticipated that these recommendations may be implemented with modifications due to other considerations. The reader is therefore cautioned to regard these recommendations as those based solely upon the results of this study.

ABSTRACT

This final report describes an experimental evaluation program which was undertaken to investigate the technical feasibility of expanding the Inter-Range Instrumentation Group (IRIG) FM/FM baseband to include a larger number of channels, choice of constant- or proportional-bandwidth subcarrier channels, and greater flexibility in operating parameters.

The program consists of: an evaluation of typical field equipment; design of an expanded proportional-bandwidth baseband, a constant-bandwidth baseband and a baseband composed of combinations of constant and proportional-bandwidth channels; and an experimental evaluation of each baseband using typical field equipment in a complete laboratory telemeter. Results are obtained for operation of the standard IRIG baseband at deviation ratios of 1, 2, and 5, as well as operation of the baseband with higher frequency channels at 93 kc, 124 kc, and 165 kc. A 21-channel constant-bandwidth baseband with channels spaced 8 kc apart from 16 kc and deviated ±2 kc is evaluated at deviation ratios of 1, 2, and 4. In addition, a baseband composed of the first 11 IRIG channels plus the 21 constant-bandwidth channels is evaluated.

Recommendations for expansion and operation of the FM/FM baseband are given as well as a discussion of the results of the system evaluation test. This report thus provides technical information which may be used by the Telemetry Working Group (TWG) of IRIG for consideration of expansion of the FM/FM baseband structure, but should in no way be considered to represent recommendations of the TWG or IRIG.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

LIST OF TABLES AND ILLUSTRATIONS
FOR VOLUME I

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME I (Cont'd.)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME I (Cont'd.)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME I (Cont'd.)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME I (Cont'd.)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME I (Cont'd.)

LIST OF TABLES AND ILLUSTRATIONS
FOR VOLUME I (Cont'd.)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II

LIST OF TABLES AND ILLUSTRATIONS
FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS
FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS
FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS
FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS
FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II (Cont'd)

LIST OF TABLES AND ILLUSTRATIONS FOR VOLUME II (Cont'd)

IDENTIFICATION OF PERSONNEL

Personnel assigned to the baseband expansion study, their primary area or contribution, and a brief resume of their backgrounds is included here:

KENNETH M. UGLOW, Chief Scientist

Mr. Uglow received the Bachelor of Science degree and a master's degree from the University of Maryland; he also studied mathematics and electromagnetic theory in the General Electric Company's advanced engineering program.

As a radio engineer with General Electric, he conducted research and development on microwave measurements and components. During World War II, he was assigned by General Electric to the Radiation Laboratory at MIT, where he participated in the development of airborne navigation and search radars.

In 1946 Mr. Uglow joined the Naval Research Laboratory. First as a project engineer in electronic instrumentation and telemetry equipment and later as electronics consultant to branches of NRL dealing with upper-atmosphere and missile research and development, he was concerned with multiplex radiotelemetry equipment and systems. For five years prior to his joining EMR, Mr. Uglow maintained a private engineering practice in Silver Spring, Maryland, dealing with telemetry equipment and system analysis and development. During this period he participated in the early phases of the tri-service study on communications systems for telemetry. This study was conducted by Aeronutronic Systems, Inc.

In 1958 he became Director of Research and Engineering at EMR. As chief scientist, Mr. Uglow serves the research and engineering functions of EMR through technical studies and consultation.

His contribution to the baseband evaluation program included analytical support and consultation on various technical problems, throughout the program.

Mr. Uglow is a member of the Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu honorary societies and is a past chairman of the IRE Professional Group of Space Electronics and Telemetry.

DR. EARL R. LIND, Manager, Telecommunication Products and Analysis Department

Dr. Lind holds BS and MS degrees from the Michigan College of Mining and Technology and a Ph.D. degree from the University of Wisconsin.

Prior to joining EMR, Dr. Lind was with the Advanced Electronics Center of the General Electric Co., Ithaca, New York.

At EMR, Dr. Lind was responsible for building and testing a simulator to analyze the combination PCM and constant-bandwidth FM multiplex performance of the test instrumentation subsystem equipment designed for the X-20 (Dyna-Soar) spacecraft. During this program he supervised the exhaustive tests performed in conjunction with RCA's X-Band transmitters and receiving equipment. At present, Dr. Lind manages the Telecommunication Products and Analysis Department. This department is responsible for the design of all EMR FM telemetry systems and equipment.

His contributions to the baseband evaluation study included advice on evaluation tests and counsel on technical problems and test results.

Dr. Lind is a member of the Institute of Electrical and Electronic Engineers, and Research Society of America, Tau Beta Pi, and Eta Kappa Nu.

MARTIN BELKIN, Section Manager, Telecommunication Products and Analysis Department

Mr. Belkin received the BSEE degree from Drexel Institute of Technology, where he participated in their cooperative education program. He has completed several University of Florida postgraduate courses.

While attending Drexel, he worked as a study engineer at the Bendix Radio Division of the Bendix Aviation Corporation and at the Missile and Space Vehicle Department of General Electric. Upon leaving college, Mr. Belkin was employed as an engineer by the Radio Corporation of America.

Since 1958, Mr. Belkin has been engaged in the design of ground station telemetry equipment at EMR. He contributed to the development of solid-state phase-locked-loop discriminators and had project responsibility for a bandswitching discriminator and a PCM signal conditioner and bit synchronizer. Mr. Belkin's responsibilities as an engineering section manager include the development of equipment for frequency multiplexed data handling systems.

Mr. Belkin's advice on ground FM equipment and instrumentation was important particularly during the planning of the systems evaluation program.

Mr. Belkin is a member of Phi Kappa Phi, Tau Beta Pi, Eta Kappa Nu, and the IEEE.

JACK E. SEITNER, Section Manager, Telecommunication Products and Analysis Department.

Mr. Seitner received the BSEE degree from Massachusetts Institute of Technology in 1950 and has taken graduate extension courses since that time.

Mr. Seitner joined EMR in 1957 and has been responsible as project engineer for the design and development of the EMR Model 210 Subcarrier Discriminator.

As an engineering section manager since mid-1963, Mr. Seitner has been responsible for the development of miniature airborne voltage-controlled and millivolt-controlled subcarrier, oscillators, frequency translators, calibrators and ancillary units.

The concept and design of the binary constant bandwidth baseband evaluated in the program was Mr. Seitner's major contribution.

Mr. Seitner has applied for patents on FM decoding systems. He is a registered professional engineer in the State of Florida.

EDWARD B. CAMPBELL, Project Engineer, Telecommunication Products and Analysis Department

Mr. Campbell received the BSEE degree with distinction from the University of Kentucky in 1958 and the MSE degree from the University of Florida in 1962. His thesis dealt with the feasibility of using frequency-locked loop principles in telemetry subcarrier discrimination.

As a design engineer at EMR, he participated in the design and development of phase-locked-loop and pulse-averaging telemetry discriminators. Mr. Campbell has participated in research programs dealing with signal conditioning equipment leading to design of the EMR 219 Signal Conditioner.

Mr. Campbell was the project engineer for the baseband expansion study and was responsible for designing the tests, supervising the project, and interpretating the results obtained.

Mr. Campbell is a member of Tau Beta Pi and Eta Kappa Nu honorary engineering societies.

WALTER R. HERBERT, Project Engineer, Telecommunication Products and Analysis Department

Mr. Herbert graduated with Bachelor and Master of Science degrees in Electrical Engineering from the Georgia Institute of Technology in 1961 and 1963, respectively, where as an undergraduate, he participated in the cooperative education program in electronic research and development with the IBM Corporation, Owego, New York. From 1961 to 1962 he served as a member of the staff of the Georgia Tech Engineering Experiment Station.

Since joining EMR he has been connected with the design and development of subcarrier discriminators as project engineer for the EMR Model 267 Subcarrier Discriminator.

Assigned to the baseband evaluation program on a full-time basis, Mr. Herbert assisted in all phases of the program, particularily the design and performance of the equipment evaluation tests and interpretation of the results obtained.

Mr. Herbert holds membership in IEEE, Tau Beta Pi, and Eta Kappa Nu.

S. KENT MORGAN, Project Engineer, Telecommunication Products and Analysis Department

Mr. Morgan received the BSEE degree with distinction from Purdue University in 1959 and the MSEE from Wisconsin in 1961, having been employed by EMR for one year in the interim.

At EMR, Mr. Morgan has been responsible for a wide range of highly specialized electronic devices and is at present project engineer responsible for a complete line of miniature FM/FM airborne equipment.

His contributions to the baseband expansion study include evaluation of the airborne equipments supplied and design and development of the constant-bandwidth equipment used.

Mr. Morgan is a member of Tau Beta Pi.

WYATT S. BISHOP, Senior Technician, Telecommunication Products and Analysis Department

Mr. Bishop received his technical training in the U.S. Navy's Aircraft Electrician school where he graduated at the head of his class.

Since discharge from the service, he has been employed by EMR and has had extensive experience in the EMR standards laboratory calibrating all types of test equipment and in the manufacturing test department performing tests on EMR products. He has been employed in the Telecommunication Products and Analysis Department for the past two years.

Mr. Bishop has been responsible for the performance of the tests conducted during the baseband expansion study.

MILLARD D. LONGMAN, Technician, Telecommunication Products and Analysis Department

Mr. Longman received his technical education at Radio Electronics Television School, Miami, Florida, graduating in 1963.

During his employment at EMR, he has worked in the manufacturing test department on the final test and qualification of digital ground stations. For the past year, he has been assigned to the Telecommunication Products Analysis Department.

His work with the baseband evaluation study has involved performance of the equipment evaluation and system tests required.

SECTION 1

INTRODUCTION

1.1 GENERAL

The Telemetry Working Group (TWG) of the Inter-Range Instrumentation Group (IRIG) recognized the need to expand the FM/FM baseband structure described in IRIG Document No. 106-60, June 1962 revision, to include a larger number of channels, choice of constant-or proportional-bandwidth subcarrier channels, and greater flexibility in operating parameters. This report describes a program funded by WSMR and the Electronic Systems Division of the USAF which was undertaken by Electro-Mechanical Research, Inc. of Sarasota, Florida, on 17 June 1964 under contract DA-29-040-AMC-746(R) to investigate the expansion of the FM/FM baseband. In essence, the program consists of an evaluation of equipment, a study to determine a feasible baseband expansion and an experimental evaluation program to verify the expansion and provide recommendations for its application.

Telemetry equipment representative of that widely used in the field was obtained and evaluated to determine those parameters which contribute to total system error. Parameters such as receiver IF-envelope-delay variation, transmitter dynamic linearity, tape-recorder harmonic distortion, etc., were measured. Where possible, similar units from different manufacturers were evaluated.

In order to determine the feasibility of the recommended expansions of the FM/FM basebands, a complete laboratory telemeter was constructed and each recommended baseband was evaluated using specific system tests. The system tests included experimental optimization of the transmitter pre-emphasis, intermodulation, signal-to-noise and system-error tests. Determination of the effect of post-detection recording, system accuracy and applicability for pulse modulation were also considered.

The format of this report includes two volumes. This volume, Volume I, summarizes the data obtained and interpretations and conclusions based upon this data. Volume II, as an appendix to Volume I, contains the detailed procedures used and the actual measured data obtained. Both volumes are subdivided into similar sections. A description of the program objectives, the overall approach, and the design of the recommended basebands are contained in Section 1 of both volumes. Section 2 in each volume discusses the equipment evaluation. The individual systems tests are treated in Section 3 of both volumes. Section 4 of Volume I contains conclusions and recommendations resulting from the program.

1.2 PROGRAM OBJECTIVES

The object of the program is to provide technical information which the TWG may use in expansion of the FM/FM baseband structure. Since any expansion of the IRIG baseband must be based on many considerations, the conclusions and recommendations resulting from the program are the technical opinions of the contractor and should in no way be considered to represent recommendations of the TWG or IRIG.

Specifically, the program was undertaken to recommend FM/FM basebands to accommodate the following data requirements:

a. A minimum of 20 continuous proportional-bandwidth channels ranging from 6 cps with a modulation index of 5 to approximately 9000 cps response with a modulation index of 1, with one or more of these channels to accommodate time multiplexing. The first 18 of these channels to be as specified in the present IRIG telemetry standards and the additional channels to conform to the approximate IRIG spacing. The added channels are to be considered for both ±7-1/2% and ±15% deviation.

b. A maximum number of constant bandwidth (1 kc or 2 kc response) channels.

c. A combination of the present IRIG standard subcarrier channels plus a maximum number of constant-bandwidth channels of 1 kc or 2 kc response.

The above basebands are to be constrained within an rf channel assignment of 500 kc measured at the 3-db points. Specifically the transmitter radiated spectrum is constrained to: the 40-db bandwidth of the modulated carrier, referenced to the unmodulated carrier, shall not exceed ±320 kc. Carrier components appearing outside a ±500 kc bandwidth shall not exceed -25 dbm.

The total rms error introduced into the data channels for the above requirements including crosstalk, intermodulation, distortion, etc., should be approximately:

a. 1 to 2% for the proportional-bandwidth channels

b. 2 to 5% for the constant-bandwidth channels

c. For the time-division channels; 0.25 to 0.75% for PDM, 2 to 5% for PAM, maximum bit error rate of 10^{-5} for PCM

Having completed the design of basebands to accommodate the above requirements, the next objective was to fabricate a complete telemeter using equipment representative of that widely used in the field to verify the feasibility of each recommended baseband. This experimental evaluation necessitates development of an evaluation program to obtain empirical data as a basis for the derivation of specific criteria for the application of the baseband configurations.

1.3 OVERALL APPROACH

The overall approach was to design the baseband configurations to meet or exceed as many of the program objectives as possible. Next, equipment representative of that in typical field use was gathered and evaluated to determine if there were any characteristics which would prohibit its use in an expanded FM/-FM baseband. A laboratory telemeter was constructed using the equipment that had been evaluated and shown to be applicable. System tests were then performed using the laboratory telemeter and the experimental baseband configurations. The feasibility and application criteria were then established for each baseband through the various system tests.

To provide a basis of comprison for the expanded-baseband configurations, the first baseband evaluated was the standard IRIG 18-channel system. In addition to this evaluation of the IRIG baseband as a reference system, its operation at deviation ratios of 1 and 2 was evaluated. The expansion of the IRIG baseband to add more proportional-bandwidth channels was undertaken next.

Having considered the expansion of the proportional-bandwidth baseband, an all constant-bandwidth-baseband configuration was experimentally evaluated using similar system tests to those performed on the proportional-bandwidth basebands. A final baseband configuration considered, using the same tests, was the combination of 11 IRIG channels with the 21 constant-bandwidth channels.

Thus, from the equipment evaluation and the system tests, the feasibility of the expansion of the FM/FM baseband was determined as well as the derivation of the various application criteria and recommendations.

1.4 DEFINITION OF SYMBOLS AND TERMS

The abbreviations and symbols below are used throughout the text.

BPIF	Band-pass input filter of subcarrier discriminator
CBW	Constant bandwidth
Crosstalk	Interference in a given channel which has its origin in another channel, e.g., adjacent channels in a frequency division multiplex system.
db	Voltage or power levels referenced to unity in decibels
dbm	Power level in db referenced to 1 milliwatt or voltage level in db referenced to the voltage into 600 ohms which dissipates 1 milliwatt
DR	Deviation ratio; in a frequency modulation system, the ratio of the maximum frequency deviation to the maximum modulating frequency of the system.

FBW	Full bandwidth
f_c	3-db cutoff frequency
f_m	Maximum modulation frequency for a particular deviation ratio
IF	Intermediate freqeuncy amplifier of receiver
Intermodulation	The modulation of the components of a complex wave by each other, producing waves having frequencies equal to the sums and differences of integral multiples of the component frequencies of the complex wave.
LPOF	Low-pass output filter of subcarrier discriminator
MI	Modulation index; for a sinusoidal modulating wave, the ratio of the frequency deviation to the frequency of the modulating wave.
PBW	Proportional bandwidth
rms transmitter deviation	Transmitter deviation sensitivity (kc peak/voltage peak) times rms voltage input.
$(S/N)_c$	Carrier-to-noise ratio
$(S/N)_d$	Signal-to-noise ratio
$(S/N)_s$	Subcarrier-to-noise ratio

1.5 BASEBAND DESIGN AND DESCRIPTION

1.5.1 Proportional Bandwidth Basebands

The design of the expanded proportional-bandwidth baseband is a direct expansion of the present IRIG configuration. The center frequencies of the higher frequency channels are approximately 1.3 times the previous upper channel. Thus, channels are located at 93 kc, 124 kc, 165 kc, 220 kc, etc. Like the present IRIG channels, it is desirable to operate all channels at ±7.5% deviation or by deleting alternate channels, operation at ±15% deviation is desirable.

There are a number of factors which limit the number of higher frequency subcarriers that can be successfully used in a multiplex, for example: decrease in subcarrier-to-noise performance or increase in intermodulation, crosstalk or harmonic distortion. The purpose of the system test using the laboratory telemeter is to determine the extent of these various errors; however, to facilitate equipment acquisition it is necessary first to make a preliminary design of the baseband. One of the more straight forward factors which limits the number of channels that can be added above 70 kc is signal-to-noise performance. To stay within the rf channel assignments with additional high-frequency subcarriers, it is necessary to reduce the transmitter deviation due to each individual VCO. This reduction in transmitter deviation alloted to each channel deteriorates the subcarrier-to-noise performance of that channel as well as the other channel in the multiplex. The problem is to determine the trade-off between the number of channels and the subcarrier-to-noise ratio in the various channels for a 500-kc receiver IF bandwidth and the transmitter radiated spectrum limit.

Using a technique proposed by H. O. Jeske,(1) the subcarrier-to-noise performance of the higher subcarrier channels can be compared to the performance of the present 70 kc channel. The results of this sideband study are shown below:

Subcarrier Frequency (kc)	Overall Performance Compared to 70 kc (db)
70	0
93	-7.1
124	-12.8
165	-22.1
220	-38.5

The above results can be interpreted as follows: for any selected criteria of system performance, the 70 kc channel can be optimized and the higher frequency channels compared to it. Thus, for a given criteria of performance, the use of the 93-kc channel will require 6.4 db or 4.5 times as much transmitter power to obtain the same performance possible with the 70 kc channel. Similarly, the 124 kc channel would require 13 times as much power and the 165 kc would

---

(1) Jeske, H. O. Extension of Proportional Bandwidth FM Subcarrier Channels, unpublished paper.

require 163 times as much power. Thus, there is a significant "knee" in the cost-function curve above 124 kc.

To define further the expansion of the baseband, a study was made to determine the required transmitter deviation that must be alloted to each subcarrier to maintain subcarrier threshold equal to or above the receiver threshold. (This is a typical design criteria often used in FM/FM telemetry.) Combining the results of this study with the maximum deviation found in the sideband study, it was concluded that it was not feasible to operate the baseband with channels above 124 kc. The details of the sideband study as well as the calculations for the maximum and minimum transmitter deviations are continued in Section 1 of Volume II.

The initial expanded proportional-bandwidth baseband considered thus contained channels at 93 kc and 124 kc; however, during the system test it was found that the 165 kc channel could be added while still maintaining the subcarrier threshold above the receiver threshold. This is discussed in more detail in the following sections. Table I-1.5-1 shows the channel allocations for the basebands evaluated using the laboratory telemeter.

1.5.2 Constant-Bandwidth Baseband

The necessity for constant-bandwidth channels arises from the need to transmit many channels with equal data response. In the proportional-bandwidth baseband, the data response ranges from 6 cps to 5 kc with a deviation ratio of 5. Systems with 10 or more sources of 1 kc data are limited in bandwidth on the low-frequency IRIG channels, and have far too much bandwidth in the higher frequency IRIG channels. The constant-bandwidth configuration provides equal data response throughout the baseband. The very nature of constant bandwidth and the need from which it arose implies the need for versatility:

a. The number of channels should be easily changed.

b. A variety of data ratios should be available.

c. Channel accuracy levels and the choice of deviation ratio available for selection of accuracy levels should be reasonable.

d. It should be possible to combine in the same baseband channels meeting difference data accuracy requirements.

Other factors which should be considered in any constant-bandwidth baseband design include:

a. Changes of tape speed in processing operations should not create incompatible channel parameters.

b. The structure should make efficient use of available rf and tape-recorder bandwidths.

c. The structure should standardize design considerations to minimize development and implementation cost.

In view of these considerations, a number of possible baseband configurations, such as the constant-bandwidth system proposed by AIA, have been eliminated from consideration for the evaluation program. In order to meet all the above requirements, the constant-bandwidth baseband structure must be derived within the following limiatations:

a. Channel center frequency allocations must be based on equal increments from dc to the highest planned channel. This restricts the choice of channel center frequencies to an integral multiple of the constant separation between channels.

b. Frequently, data is recorded at one tape speed and played back at a different speed. Since tape speeds are binarily related, it is desirable for the channel center frequency allocations also to be binarily related. In this manner, tape-speed changes do not create nonstandard channel frequencies.

c. Standard data-cutoff frequencies and deviation ratios should be binarily related to minimize the number of standard discriminator output filters required.

Table I-1.5-2 shows a construction table for a constant-bandwidth baseband configuration based on the binary relationship. The first row in Table I-1.5-2 shows the incremental spacing for possible channel positions starting at dc. The second row contains the basic channel numbers for the binary system. The basis for the third row of channel center frequency is a channel separation of 4 kc per 1 kc of peak-frequency deviation, which has been shown to provide an optimum compromise between bandwidth efficiency and accuracy levels for deviation ratios of 1, 2, 4, and 8. Thus, for the ±2 kc deviation system, the channel spacing is 8 kc with the first channel (optional Channel A) at 8 kc.

As an example of the use of Table I-1.5-2, consider the system design shown in the fourth row. This is a 21-channel system with ±2 kc deviation. The example is a ground station configuration which assumes that the airborne system has been previously implemented. The first six channels are direct channels, i.e., no translation is required. The next five channels (7 through 11) are heterodyned with a 120-kc signal which places the difference-frequency band in the position of Channels 2 through 6. Channels 7 through 11 are thus translated and then demodulated by subcarrier discriminators operating at frequencies from 24 kc to 56 kc. The remaining channels are translated in groups of five in an identical manner. The heterodyne signals are synthesized from the tape-speed-compensation reference tone at 240 kc. Although the example was for a ground system, the airborne system can be constructed in an identical manner by reversing the translation procedure. Several other examples are also shown in Table I-1. 5-2. Table I-1. 5-3 shows a chart of the possible operating parameters of the binary constant-bandwidth configuration.

As illustrated in Tables I-1. 5-2 and I-1. 5-3 a baseband comprising almost any number of channels can be implemented with the binary structure using channels in the group 1 through 6 for the basic subcarrier-oscillator and discriminator frequencies. These channels have percentage frequency deviations within the range of ±3.7% to ±12.5% which are within the capabilities of available equipments. For instrumentation systems utilizing "two-group" frequency translation, the number of channels in the baseband is not limited as a result of uneven channel separation, as in the case of the AIA recommendation, and 8-, 10-, and 12-channel systems are possible. Translation systems consisting of more than two groups can be easily derived from the binary structure shown in Table I-1. 5-2. Because of the continuous channel-frequency assignment, the heterodyne signals required for detranslation can easily be synthesized from a recorded reference tone. All translated groups consist of the same number of subcarriers yielding standardized filter designs and equal delay to the modulation of all channels. Undesired translation sidebands and harmonic signals can be suppressed to acceptable levels by practical filters. The implementation and expansion advantages of the binary system are not provided by the AIA constant-bandwidth recommendation because of discontinuities in channel frequency assignment, as shown in Figure I-1. 5-4.

Through the use of the sideband study mentioned in the previous section, the maximum transmitter deviation due to a particular subcarrier channel was determined as well as the minimum deviation to cause the subcarrier discrimination to threshold at the same carrier level. The maximum constant-bandwidth subcarrier center frequency was found to be 180 kc. Thus, the constant-bandwidth baseband configuration which most nearly meets the objectives of the baseband expansion and which was chosen for evaluation is the 21-channel system of Table I-1. 5-2 with the highest frequency channel at 176 kc. The channel allocations and implementation for this baseband are shown in Table I-1. 5-5. In addition to the 21-channel system, the 11-channel and 5-channel configurations shown in Table I-1. 5-2 are also recommended for transmission in the standard IRIG VHF band. The performance and versatility of these basebands is shown in Table I-1. 5-6.

1. 5. 3 Combinational-Bandwidth Baseband System

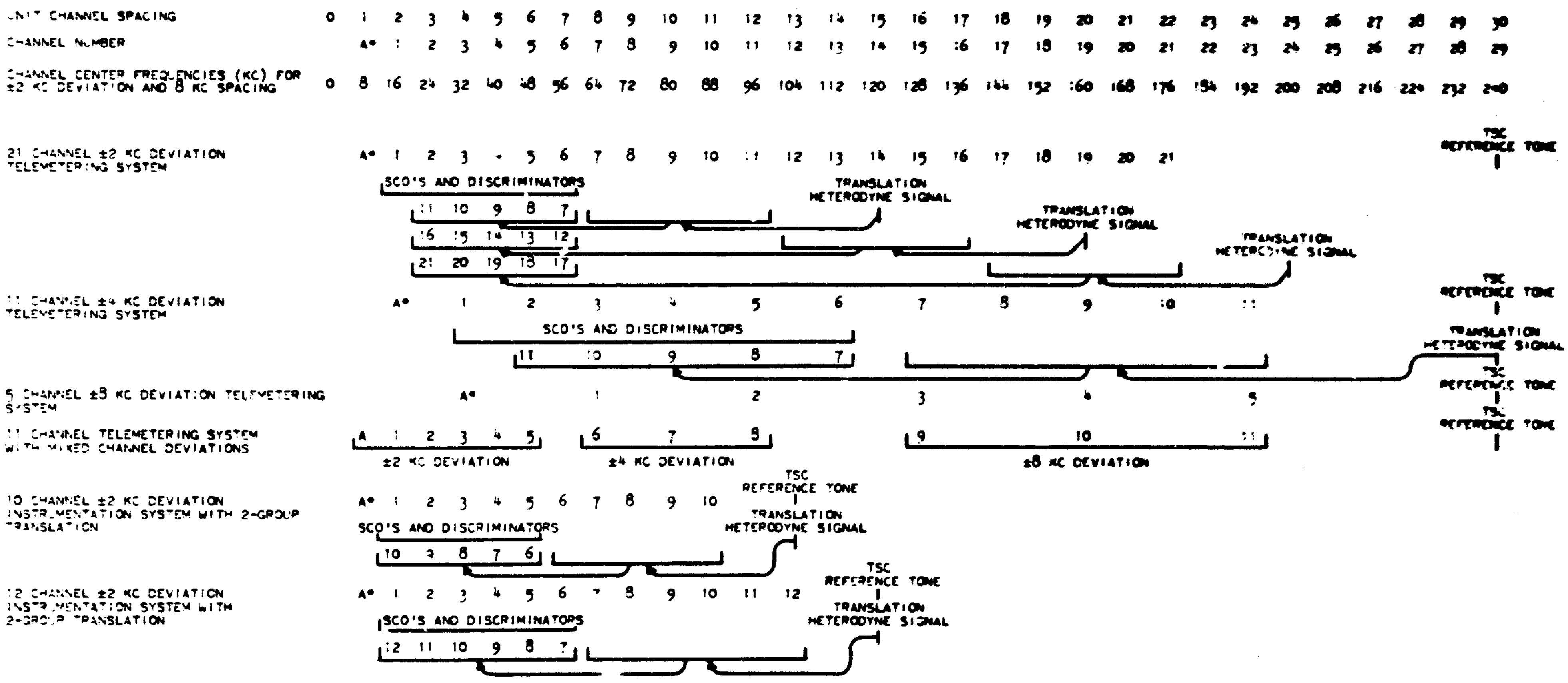
To meet the objective of a baseband providing both constant- and proportional-bandwidth channels, the combinational-bandwidth baseband system was designed and evaluated. This baseband consists of taking the 21-channel constant-bandwidth baseband and filling the space between dc and the first constant bandwidth channel at 16 kc with IRIG proportional-bandwidth channels.

With the ±2-kc constant-bandwidth channels spaced 8 kc apart, the guard-band limit associated with each channel is 2 kc or ±4 kc from band center. For the 16-kc channel, this guard band extends to 12 kc. The center of the guard band between IRIG channel 12 (10.5 kc ±7.5%) and channel 13 (14.5 kc ±7.5%) is 12.3 kc, which is above the 12-kc guard-band edge for the first constant-bandwidth baseband channel.

Thus, the highest IRIG channel used in the combinational bandwidth baseband is channel 11 (7.35 kc ±7.5%). The combinational bandwidth baseband thus consists of IRIG channels 1 through 11, Table I-1.5-1 and constant-bandwidth channels 1 through 21, Table I-1.5-5.

TABLE I-1.5-1
CHANNEL ALLOCATIONS FOR PROPORTIONAL BANDWIDTH BASEBANDS

Center Frequency (kc)	IRIG Baseband	IRIG Baseband with Wideband Channel	Expanded Proportional Bandwidth Baseband	Expanded Proportional Bandwidth Baseband with Wideband Channel
0.40	1 ±7.5%	1 ±7.5%	1 ±7.5%	1 ±7.5%
0.56	2 ±7.5%	2 ±7.5%	2 ±7.5%	2 ±7.5%
0.73	3 ±7.5%	3 ±7.5%	3 ±7.5%	3 ±7.5%
0.96	4 ±7.5%	4 ±7.5%	4 ±7.5%	4 ±7.5%
1.30	5 ±7.5%	5 ±7.5%	5 ±7.5%	5 ±7.5%
1.70	6 ±7.5%	6 ±7.5%	6 ±7.5%	6 ±7.5%
2.30	7 ±7.5%	7 ±7.5%	7 ±7.5%	7 ±7.5%
3.00	8 ±7.5%	8 ±7.5%	8 ±7.5%	8 ±7.5%
3.90	9 ±7.5%	9 ±7.5%	9 ±7.5%	9 ±7.5%
5.40	10 ±7.5%	10 ±7.5%	10 ±7.5%	10 ±7.5%
7.35	11 ±7.5%	11 ±7.5%	11 ±7.5%	11 ±7.5%
10.5	12 ±7.5%	12 ±7.5%	12 ±7.5%	12 ±7.5%
14.5	13 ±7.5%	13 ±7.5%	13 ±7.5%	13 ±7.5%
22.0	14 ±7.5%	14 ±7.5%	14 ±7.5%	14 ±7.5%
30.0	15 ±7.5%	15 ±7.5%	15 ±7.5%	15 ±7.5%
40.0	16 ±7.5%	16 ±7.5%	16 ±7.5%	16 ±7.5%
52.5	17 ±7.5%	—	17 ±7.5%	17 ±7.5%
70.0	18 ±7.5%	E ±15%	18 ±7.5%	18 ±7.5%
93.0	—	—	19 ±7.5%	19 ±7.5%
124.0	—	—	20 ±7.5%	—
165.0	—	—	21 ±7.5%	H ±15%



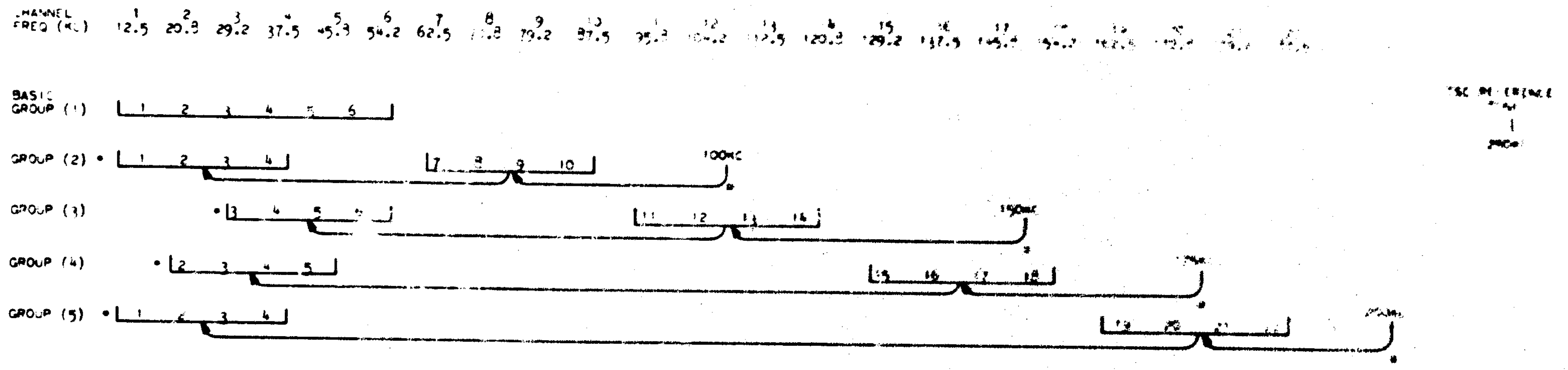
* ALTERNATE CHANNEL - PERFORMANCE MAY BE DEGRADED DUE TO ±25% FULL-SCALE FREQUENCY DEVIATION.

SYSTEMS WITH MORE CHANNELS OR INCREASED DEVIATION MAY BE DEVELOPED BY BINARY EXPANSION AS EXAMPLIFIED ABOVE.

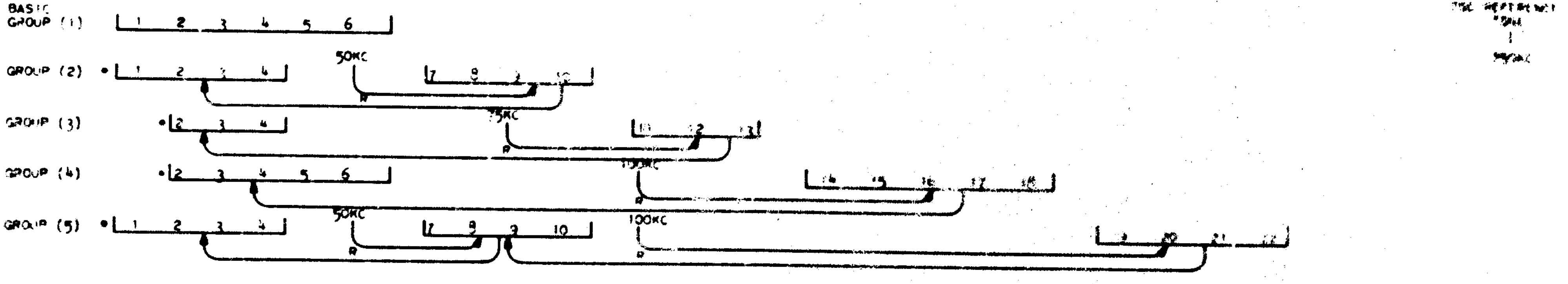
TABLE I-1.5-2
CONSTRUCTION OF BINARY CONSTANT BANDWIDTH BASEBANDS

TABLE I-1. 5- 3
STANDARDIZED OPERATING PARAMETERS FOR BINARY CONSTANT BANDWIDTH BASEBANDS

Full-Scale Frequency Deviation	Deviation Ratio	Data Cutoff Frequency	Channel Sepatation
±1 kc	1	1 kc	4 kc
	2	500 cps	
	4	250 cps	
	8	125 cps	
±2 kc	1	2 kc	8 kc
	2	1 kc	
	4	500 cps	
	8	250 cps	
±4 kc	1	4 kc	16 kc
	2	2 kc	
	4	1 kc	
	8	500 cps	
±8 kc	1	8 kc	32 kc
	2	4 kc	
	4	2 kc	
	8	1 kc	
±16 kc	1	16 kc	64 kc
	2	8 kc	
	4	4 kc	
	8	2 kc	
±32 kc	1	32 kc	128 kc
	2	16 kc	
	4	8 kc	
	8	4 kc	



a) EMR DETRANSLATION TECHNIQUE



B) AIA DETRANSLATION TECHNIQUE (1)

LEGEND:
R: SYNTHESIZED HETERODYNE REFERENCE SIGNALS
*: TRANSLATES TO
(1): ATC REPORT NO. ARTC-39 "DEVELOPMENT OF A CONSTANT BANDWIDTH FM STANDARD", AEROSPACE INDUSTRIES ASSOCIATION

FIGURE I-1.5-4
CONSTRUCTION OF AIA CONSTANT BANDWIDTH BASEBANDS

TABLE I-1.5-5
CHANNEL ALLOCATIONS FOR CONSTANT BANDWIDTH BASEBAND

Channel Number	Group	VCO Frequency (kc)	Translation Frequency (kc)	Channel Frequency (kc)
1	A	16	None	16
2		24		24
3		32		32
4		40		40
5		48		48
6		56		56
7	B	56	120	64
8		48		72
9		40		80
10		32		88
11		24		96
12	C	56	160	104
13		48		112
14		40		120
15		32		128
16		24		136
17	D	56	200	144
18		48		152
19		40		160
20		32		168
21		24		176

TABLE I-1.5-6
RECOMMENDED CONSTANT BANDWIDTH BASEBAND CONFIGURATIONS

Number of Subcarrier Channels	Subcarrier Deviation	Subcarrier Separation	Deviation Ratio	Data Cutoff Frequency
21	±2 kc	8 kc	1	2 kc
			2	1 kc
			4	500 cps
			8	250 cps
11	±4 kc	16 kc	1	4 kc
			2	2 kc
			4	1 kc
			8	500 cps
5	±8 kc	32 kc	1	8 kc
			2	4 kc
			4	2 kc
			8	1 kc

SECTION 2

EQUIPMENT EVALUATION

2.1 GENERAL

One of the objectives of the baseband-expansion program was to determine if typical field-equipment performance characteristics will prevent expansion of the standard IRIG baseband. To this end, an equipment evaluation was undertaken to ascertain those characteristics which would contribute significant errors to an expanded-baseband system. The results of the equipment evaluation also enable the extrapolation of the system tests to other field equipment not specifically used in the laboratory telemeter. The equipment evaluation tests are thus designed to evaluate parameters contributing to system errors rather than a verification of manufacturers specifications.

The results of the equipment evaluation test are summarized in the following sections. The measured data as well as the detailed test procedures are contained in Section 2 of Volume II.

2.2 VOLTAGE-CONTROLLED OSCILLATORS

An evaluation program measuring static and dynamic linearity, modulation feedthrough, total harmonic distortion, and crosstalk was undertaken to establish the general operational capability of the VCO's to be used in the study. Five units from the 38 GFE units, Tele-Dynamics Model 1270A, and Vector Model TS-41 and -41-HF, and an EMR Model 307A, were tested. Detailed results and procedures are contained in Section 2.2 of Volume II. A brief summary of the maximum and minimum measurements is included as Table I-2.2-1 to reveal the performance level of the VCO's used in the evaluation program. Voltage-controlled oscillators of the type evaluated present no hinderance at all to expansion of the baseband.

TABLE I-2.2-1

VCO EVALUATION SUMMARY

	Max.	Min.
Static Linearity (Best Straight Line)	±0.12% of BW	±0.019% of BW
Dynamic Linearity (Best Straight Line)	±0.05% of BW	±0.01% of BW
Modulation Feedthrough, MI = 1 (Percent of unmodulated VCO output voltage)	0.87%	0.0048%
Total Harmonic Distortion (Percent of unmodulated VCO output voltage)	0.64%	0.07%
Crosstalk	Negligible on all units.	

2.3 MIXER AMPLIFIER

The Sonex Model TEX-3210 Mixer Amplifier was evaluated to establish its general performance characteristics with regard to its capability for use with baseband configurations extending to 200 kc. Results are summarized as follows:

Amplitude response	Within ±0.5 db from 200 cps to 200 kc
Harmonic content (maximum) relative to fundamental	2nd -44.0 db 3rd -54.5 db 4th -68.0 db
Intermodulation products (maximum)	14.5 kc and 22 kc; 0.008% of 1.0 volt rms full multiplex output

The results of the test show that the Model TEX-3210 is suitable for use in an expanded FM/FM baseband.

Detailed results and block diagrams of the tests are included in Section 2.3 of Volume II.

2.4 GROUP FREQUENCY TRANSLATOR

The EMR Model 316 Frequency Translator is used in constant-bandwidth systems to generate stable high-frequency subcarrier channels by translating the outputs of several standard, lower-frequency subcarrier voltage-controlled oscillators to higher center frequencies. Since the Model 316 was specifically designed for constant-bandwidth application, no detailed equipment evaluation was undertaken as part of this study; however, its operation within specification was verified by other EMR personnel throughly familiar with the unit. Specifications directly affecting baseband performance and channel accuracy are summarized as follows:

Acceptable Subcarrier Frequencies:	4 kc to 750 kc.
Subcarrier Frequency Deviation:	±1 kc to ±16 kc.
Spurious Output Signals:	Individual spurious output signals are -46 db or less referenced to the nominal individual subcarrier output level.

A more complete description of the unit and its specifications are contained in Volume II, Section 2.4.

2.5 TRANSMITTER

Two telemetry transmitters, an EMR Model 121D and a Leach Model FM200, representative of those units in current field use, were evaluated for deviation sensitivity and harmonic distortion at higher modulation frequencies and deviations. Harmonic distortion results are presented in Figure I-2.5-1 for the EMR Model 121D and Figure I-2.5-2 for the Leach Model FM200. For modulation frequencies up to 70 kc, the EMR Model 121D was found to exhibit THD equivalent or superior to the Leach unit, but its performance deteriorated at higher modulation frequencies. As a result, the Leach Model FM200 was selected for use in the laboratory telemeter.

Deviation sensitivity was found to be a marked function of frequency above 70 kc for both the EMR 121D and Leach FM200 Transmitters. Figures I-2.5-3 and I-2.5-4 present the measured data; Figures I-2.5-5 and I-2.5-6 illustrate graphically the sensitivity decrease above 70 kc. Because of this rolloff, a nominal deviation sensitivity of 75-kc-per-volt was used throughout the study. This sensitivity rolloff was not an insurmountable obstacle to expansion of the baseband. Account having been taken of this characteristic and a correction allowed when considering relative subcarrier levels, as in discussions of pre-emphasis, the transmitter was adequate for expanded-baseband use. A block diagram of the test and the measured data are contained in Volume II, Section 2.5.

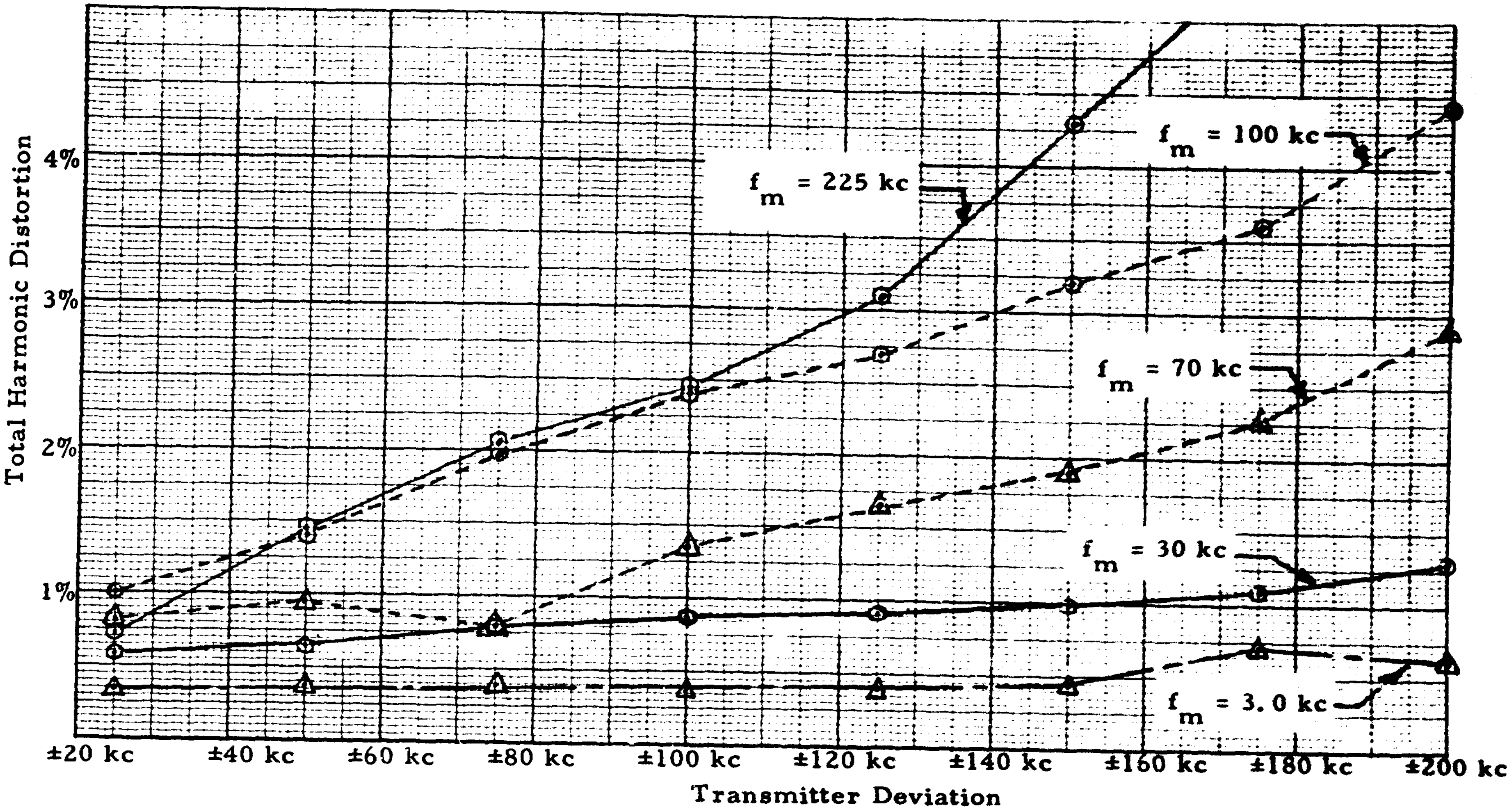


FIGURE I-2.5-1
TOTAL HARMONIC DISTORTION, EMR 121D

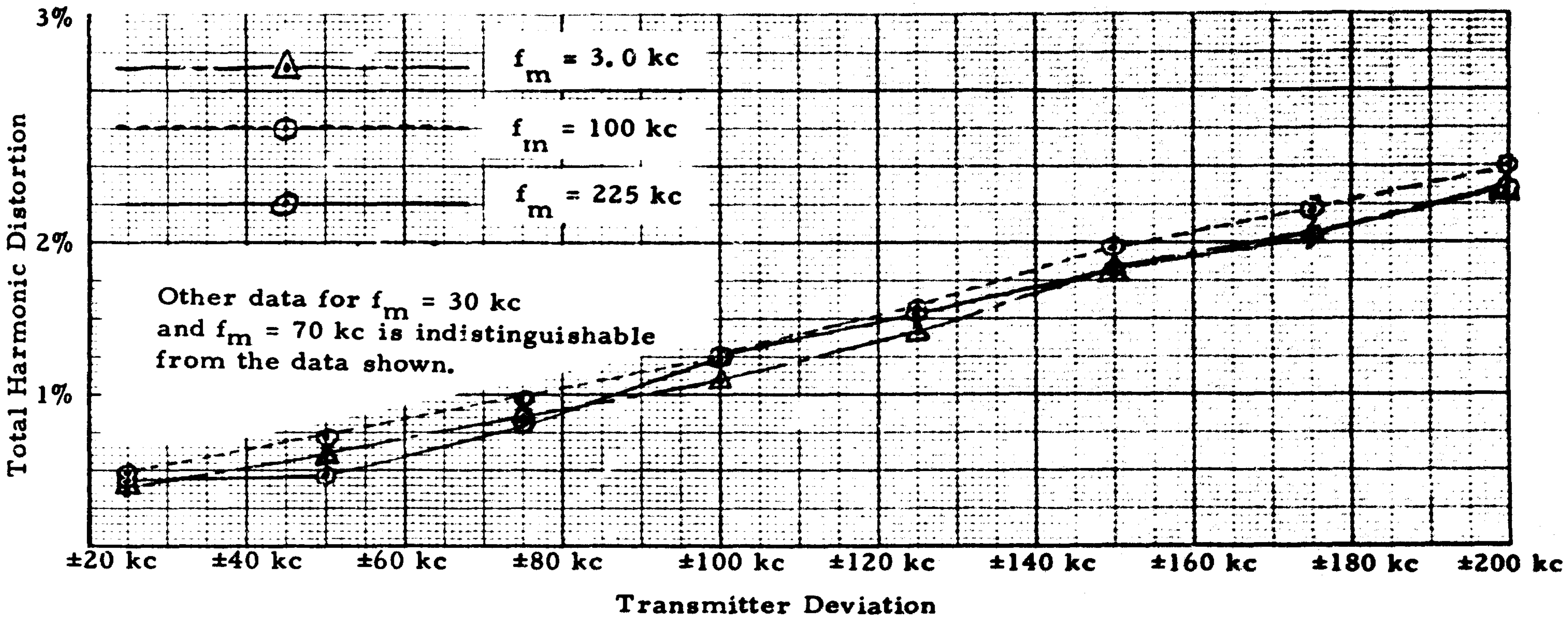


FIGURE I-2. 5-2
TOTAL HARMONIC DISTORTION, LEACH FM 200

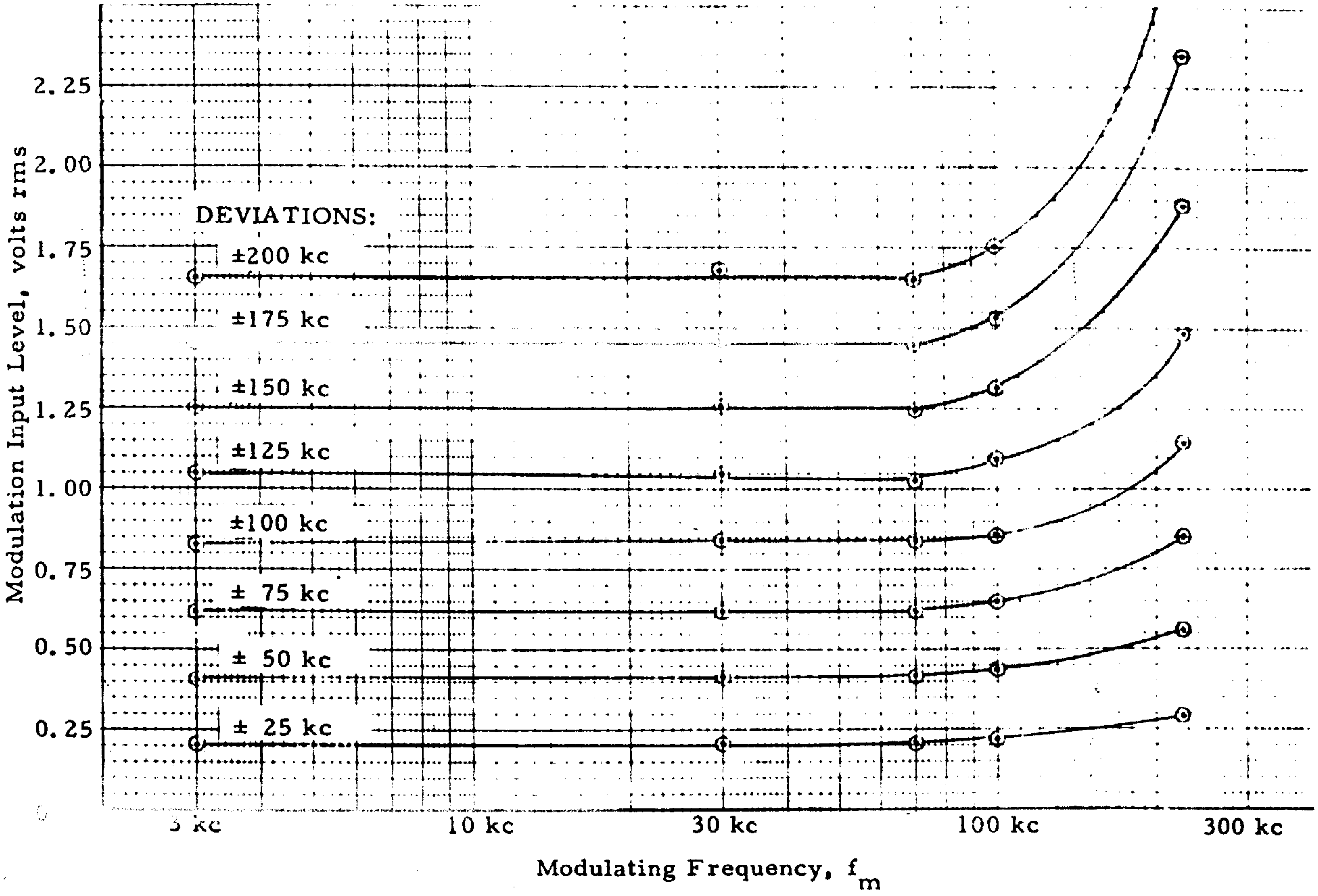


FIGURE I-2.5-3
DEVIATION SENSITIVITY, EMR 121D

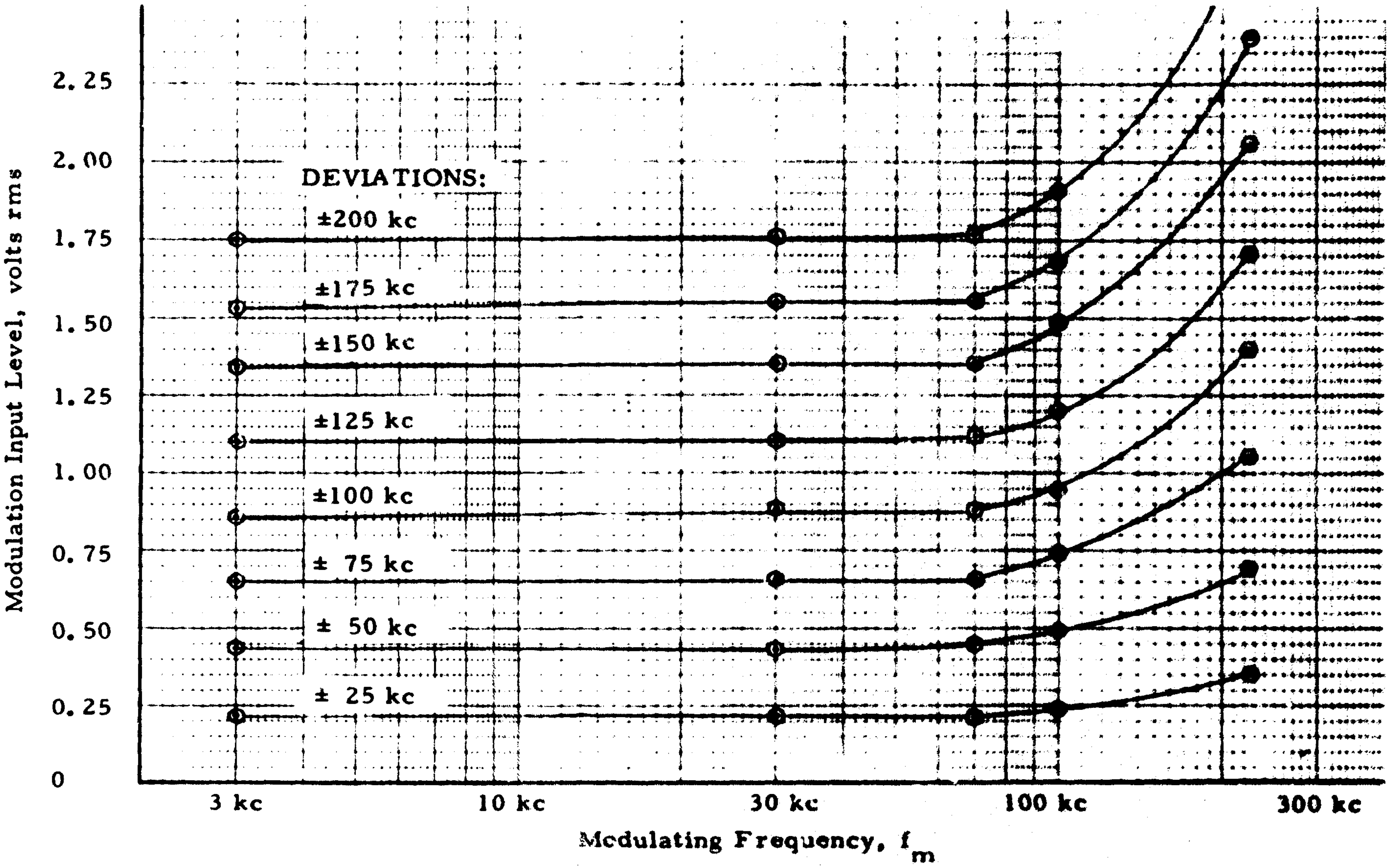


FIGURE 1-2.5-4
DEVIATION SENSITIVITY, LEACH FM 200

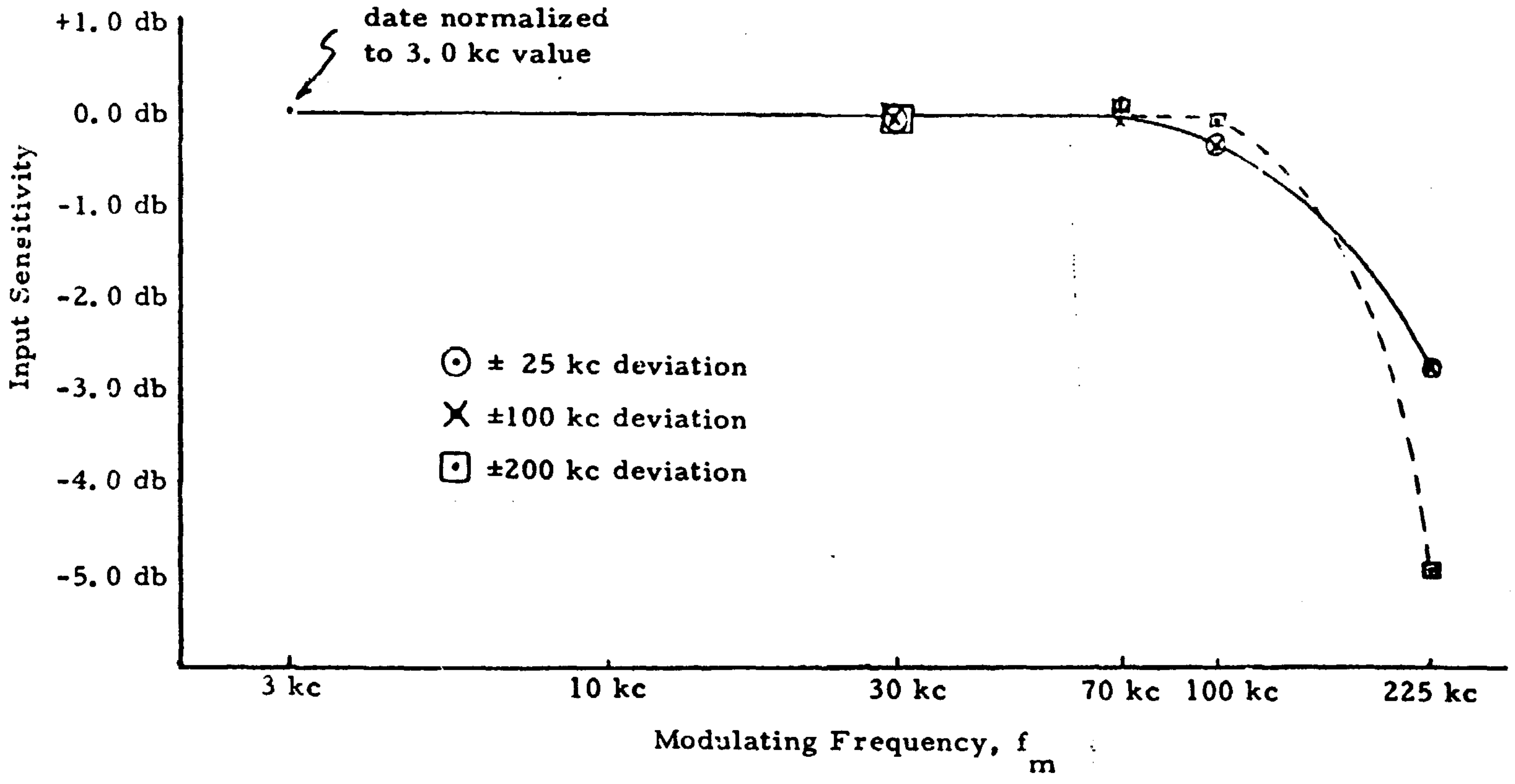


FIGURE I-2. 5-5
NORMALIZED DEVIATION SENSITIVITY, EMR 121D

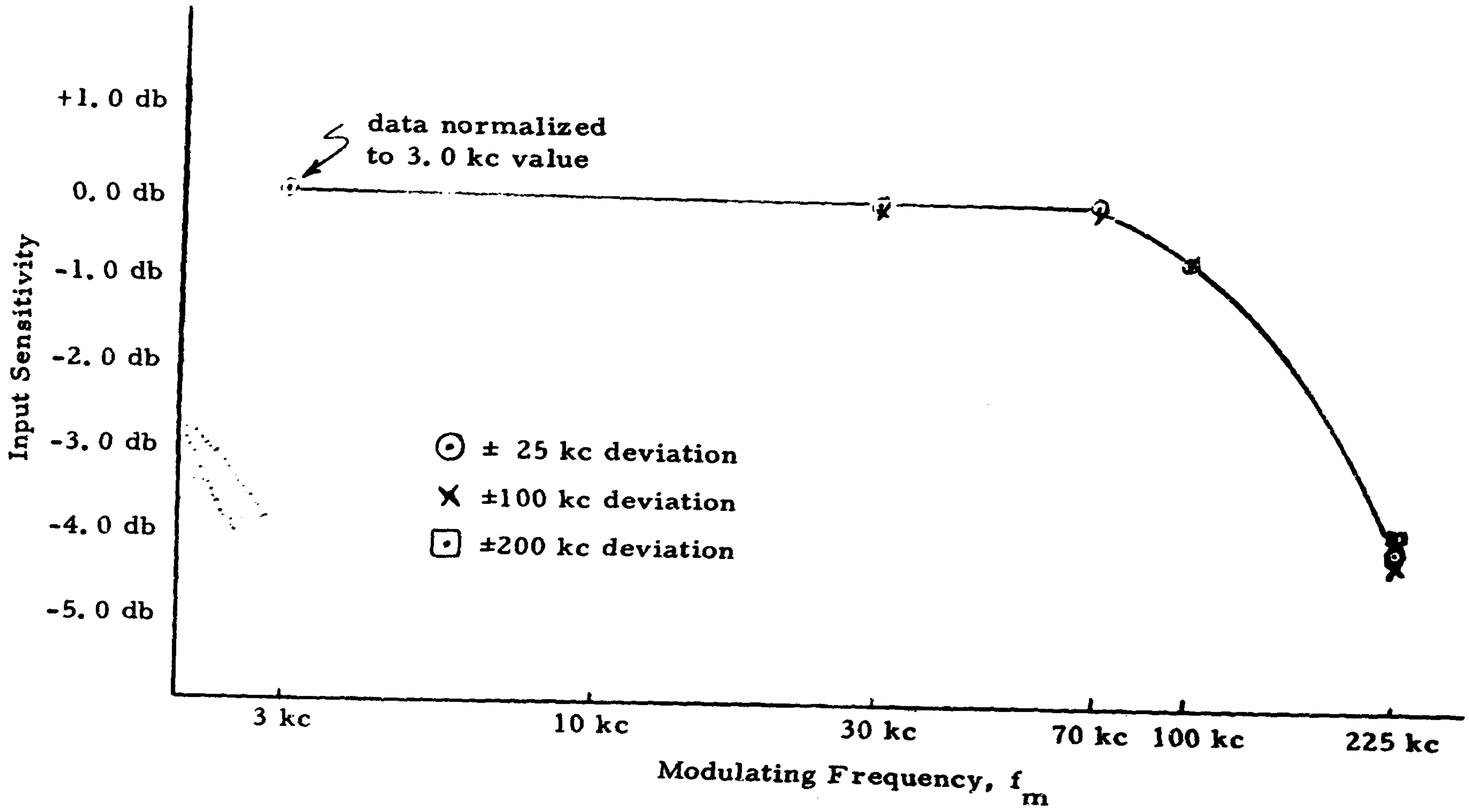


FIGURE I-2. 5-6
NORMALIZED DEVIATION SENSITIVITY, LEACH FM 200

2.6 RECEIVER

2.6.1 General

The receiver characteristics which contribute to system error were measured on each of two telemetry receivers, a Nems-Clarke (Vitro) Model 1455A and a Defense Electronics Model TMR-2A. Intermediate frequency (IF) amplifier amplitude response and intelligence time-delay characteristics and receiver output-noise density as a function of carrier-to-noise ratio were measured on both units. The Nems-Clarke unit, which was available for a longer period and was used in the telemeter system evaluation, was evaluated for harmonic distortion in combination with an EMR 121D Transmitter to establish whether the unit's Foster-Seeley or phase-lock detector should be used in the system evaluation.

2.6.2 IF Amplifier Characteristics

Both receivers evaluated were equipped with 500-kc-bandwidth IF amplifiers. Each was evaluated as to frequency response, especially in the passband, and intelligence time-delay variation across the passband. Results obtained are presented in Figures I-2.6-1 and I-2.6-2. Difficulty was experienced in measuring the Defense Electronics TMR-2A's 10 Mc IF Amplifier over a large dynamic range, thus the data is incomplete on the skirt of the pass band. Intelligence time-delay variation was found to be less by a factor of three with the TMR-2A than with the 1455A.

Original data and the procedures used in obtaining it are discussed in detail in Volume II, Section 2.6.2.

2.6.3 Output Noise Density

Output noise density was measured as a function of carrier-to-noise ratio on each of the receivers with results shown in Figures I-2.6-3 and I-2.6-4.

This data illustrates how the character of the output noise changes with the carrier-to-noise ratio.

2.6.4 Total Harmonic Distortion (THD)

Using the EMR Model 121D Transmitter in combination with the Nems-Clarke Model 1455A Receiver, total harmonic distortion data was obtained for each of the receiver's two FM detectors, Foster-Seeley and phase-lock. Data obtained (Figures I-2.6-5 and I-2.6-6) indicate the Foster-Seeley detector to be superior to the phase-locked detector for wide deviations and high modulation frequencies. Quantitative measurements of receiver THD were masked by the distortion of the transmitter used in combination with it. Details of the test are contained in Volume II, Section 2. 6. 4.

2. 6. 5 Intermodulation Distortion

Intermodulation data was obtained using the Leach Model FM200 Transmitter in combination with the Nems-Clarke Model 1455A receiver. Assuming a linear pre-emphasis, two pairs of subcarrier frequencies were evaluated as to intermodulation products: 52. 5 kc with 70 kc and 93 kc with 124 kc. Results obtained at the difference frequency are presented in Figure I-2. 6-7 as a function of peak transmitter deviation due to the higher frequency primary signal. Measured data is contained in Volume II, Section 2. 6. 5.

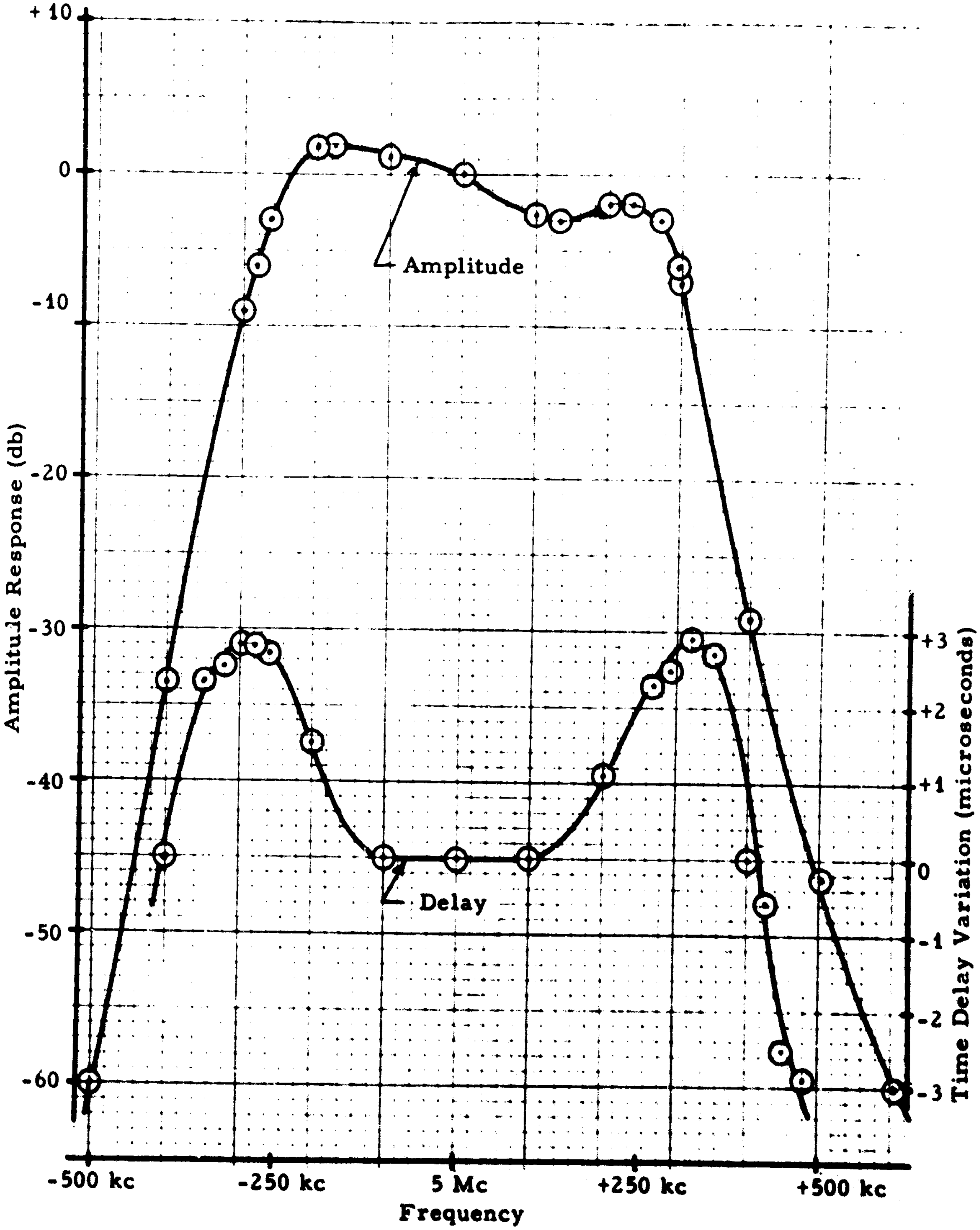


FIGURE I-2.6-1
IF AMPLIFIER CHARACTERISTICS, NEMS CLARKE (VITRO) 1455A

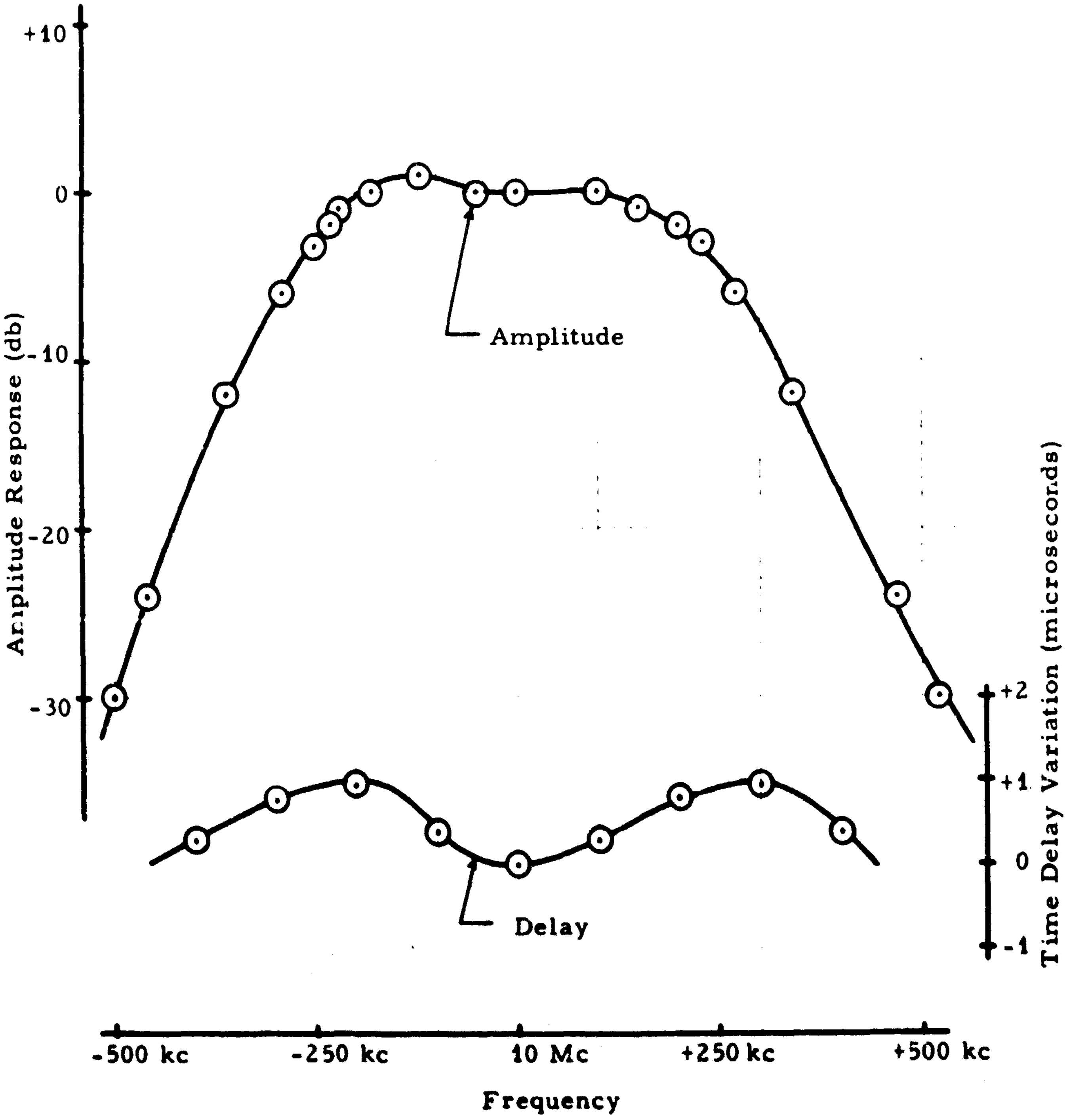


FIGURE I-2.6-2

IF AMPLIFIER CHARACTERISTICS, DEFENSE ELECTRONICS TMR-2A

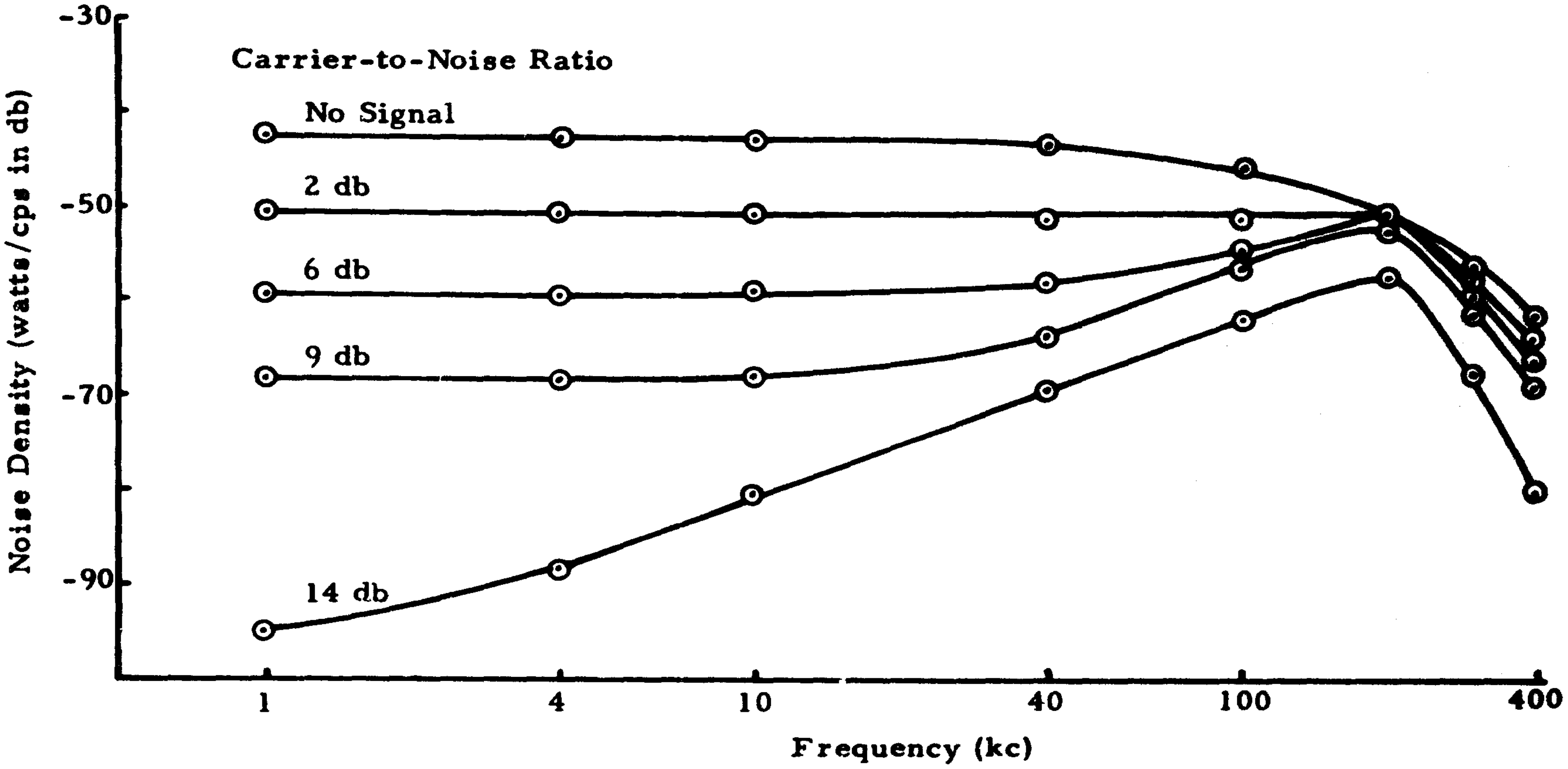


FIGURE I-2.6-3
OUTPUT NOISE DENSITY, NEMS-CLARKE 1455A

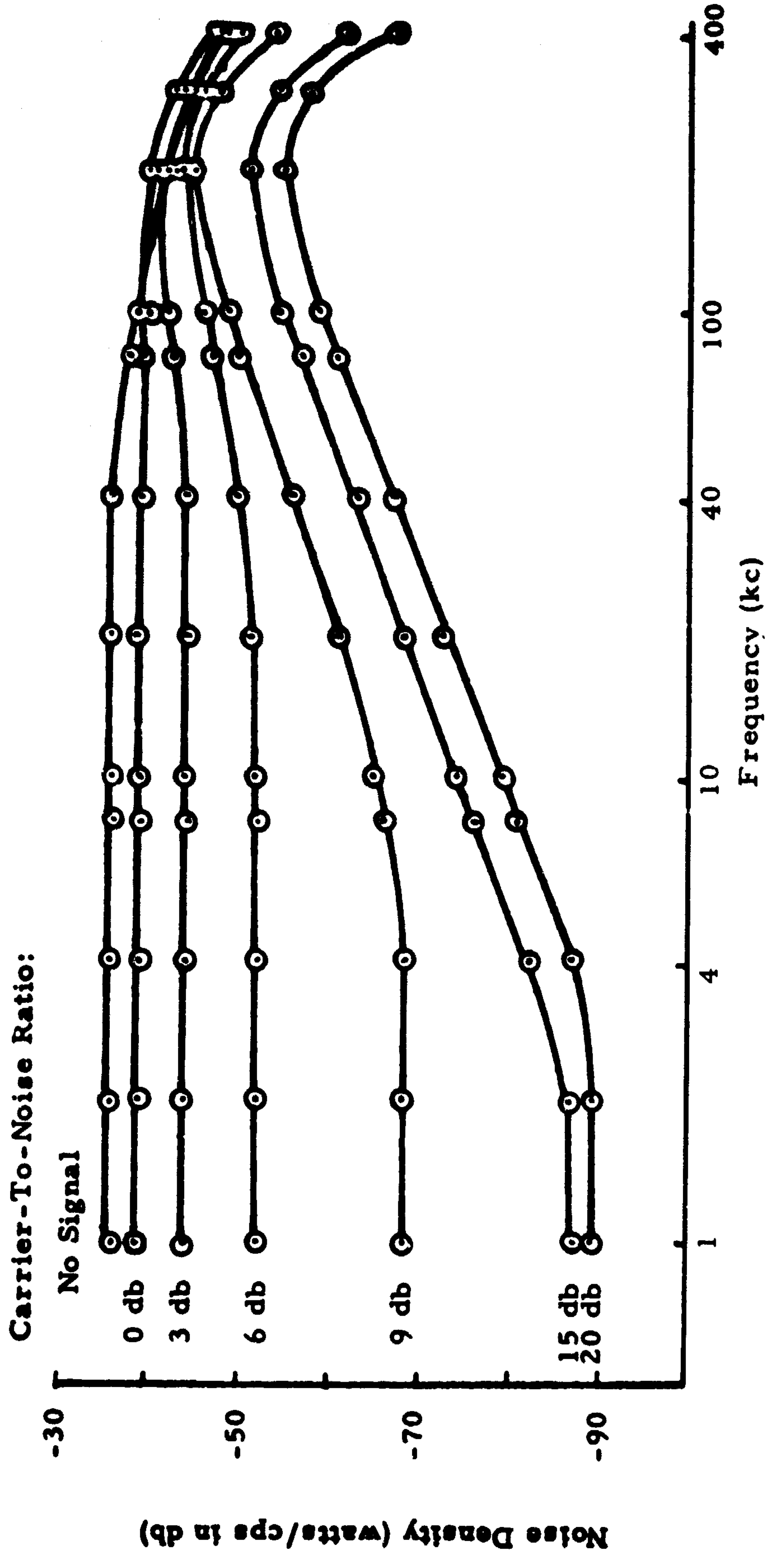


FIGURE I-2.6-4
OUTPUT NOISE DENSITY, DEFENSE ELECTRONICS TMR-2A

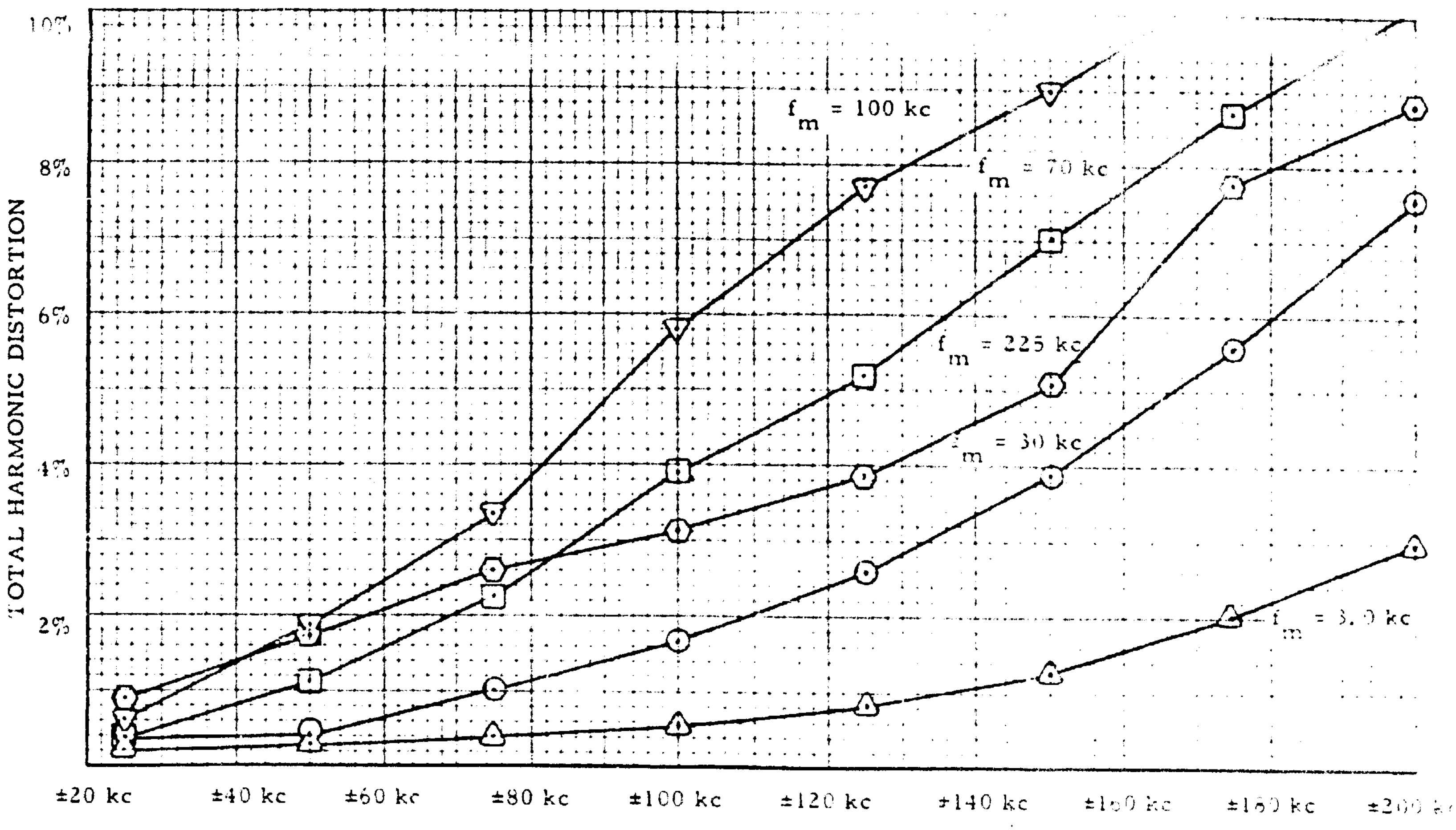


FIGURE I-2.6-5
TOTAL HARMONIC DISTORTION
TRANSMITTER/RECEIVER COMBINATION
EMR 121D/NEMS-CLARKE 1455A (FM DETECTOR)

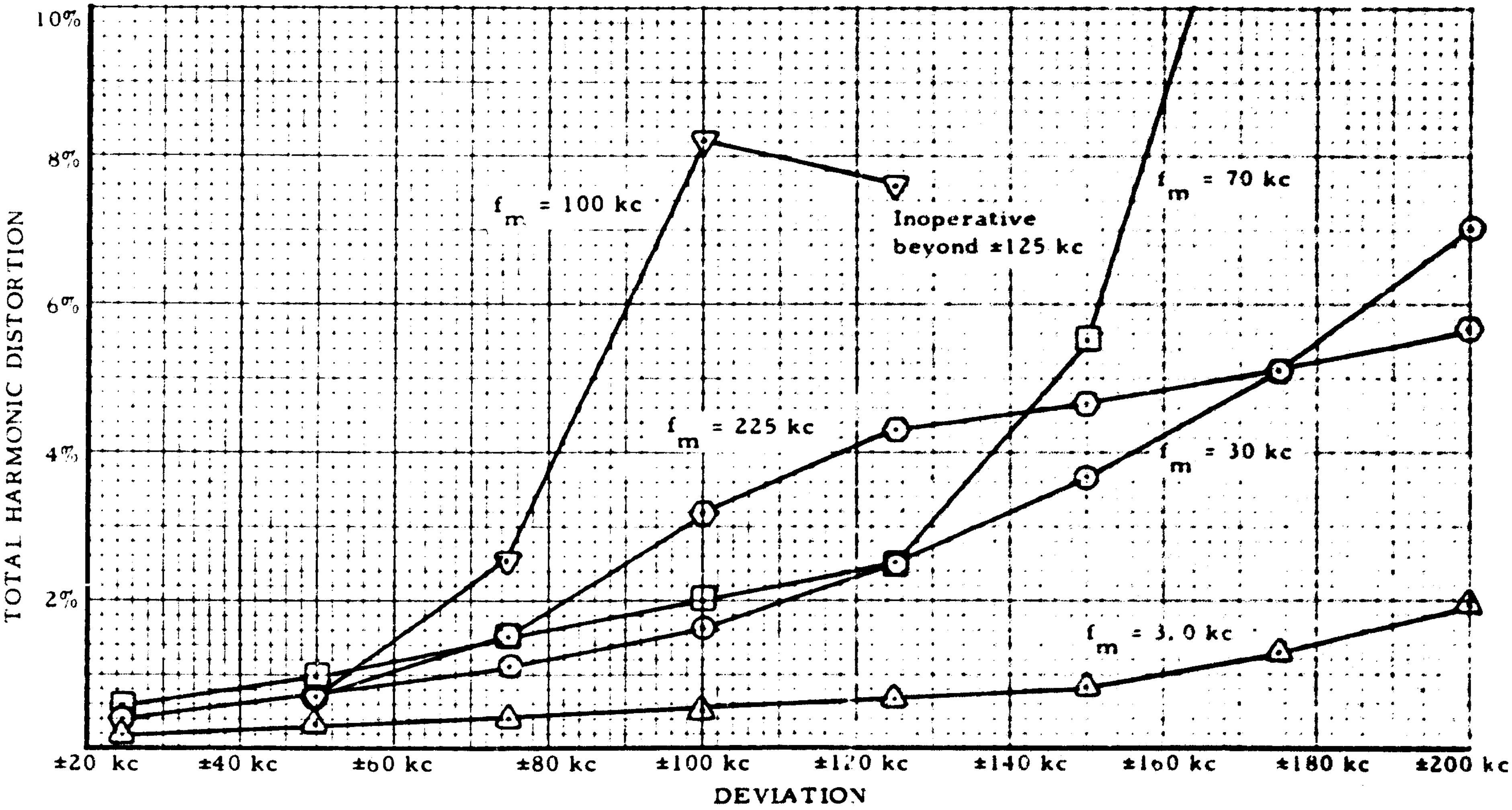


FIGURE I-2.6-6
TOTAL HARMONIC DISTORTION
TRANSMITTER/RECEIVER COMBINATION
EMR 121D/NEMS-CLARKE 1455A (PHASE-LOCKED LOOP)

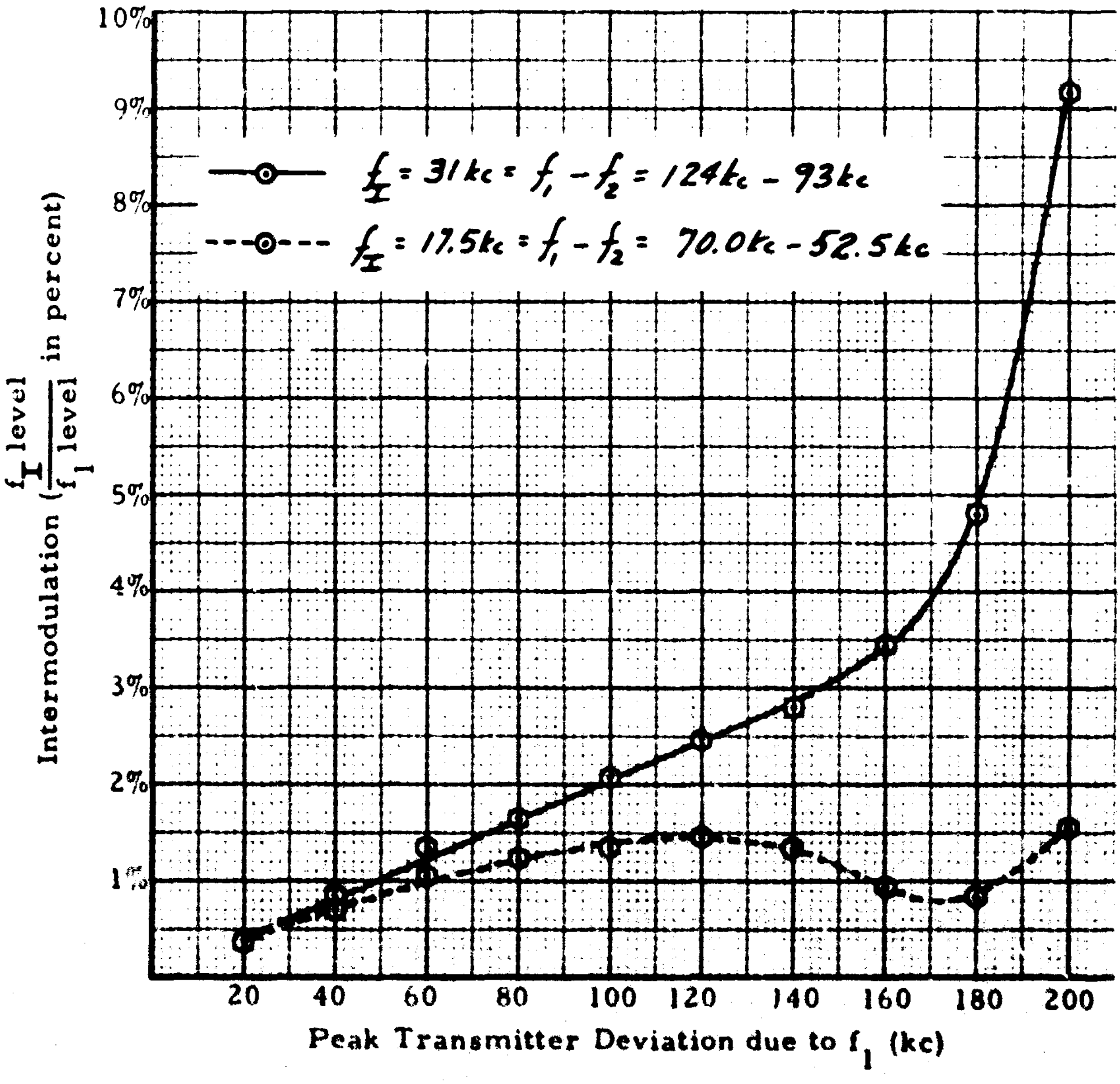


FIGURE I-2. 6-7
DIFFERENCE FREQUENCY INTERMODULATION,
LEACH FM 200 AND NEMS-CLARKE 1455A

2.7 GROUP FREQUENCY DETRANSLATOR

In the constant-bandwidth baseband evaluation, the newly developed EMR Model 259 Modular Group Frequency Detranslator was used to translate portions of the receiver output multiplex into groups of lower-frequency multiplexed subcarriers for direct application to the subcarrier discriminators. No evaluation program as part of the study contract was undertaken for this unit as it was specifically designed for constant-bandwidth applications; however, its operation within specification was verified by other EMR personnel. Condensed specifications affecting channel performance and the baseband expansion study are summarized as follows:

Subcarrier Frequencies: A multiplex of FM subcarrier frequencies in the range from 5 kc to 1100 kc is converted into groups of subcarriers suitable for direct application to subcarrier discriminators.

Data Time Correlation: Data-channel time errors contributed by the Model 259 Group Frequency Detranslator are less than $\pm 1^{\circ}$ from the BSL delay at a deviation ratio of 2 or greater.

Intermodulation Distortion: Intermodulation distortion products, at normal input level, each are less than 0.5% of the amplitude of any subcarrier.

Subcarrier Feedthrough: For flat subcarrier emphasis, lower group subcarriers in the detranslated group outputs are suppressed at least 46 db.

Image Rejection: For flat subcarrier emphasis, images of undesired groups which appear in the desired group are suppressed at least 46 db.

2.8 SUBCARRIER DISCRIMINATOR

A separate evaluation program was not undertaken for the EMR Model 210 Subcarrier Discriminators used in the study. Prior to use, each unit was retested by EMR's manufacturing test department to certify its operation within specification. Specifications of direct importance to the baseband evaluation study and similar to those specifications measured on other equipments are as shown in Table I-2.8-1. Normalized frequency response characteristics of the EMR Model 210's loop amplifier and band-pass input filter are given in Figure I-2.8-2. Normalized response characteristics of the discriminator low-pass output filter are shown in Figure I-2.8-3. The discriminator is completely compatible with the expanded and constant-bandwidth baseband requirements and should present no restriction to baseband expansion.

TABLE I-2. 8-1
SPECIFICATION SUMMARY EMR 210 SUBCARRIER DISCRIMINATOR

	DR = 5	DR = 2
Total Harmonic Distortion	$<$ 0. 5%	$<$ 1. 3%
Output Noise (rms % of FBW peak-to-peak voltage)	$<$ 0. 05%	$<$ 0. 10%
Linearity (percent of FBW, best straight line)	±0. 05%	±0. 05%
Dynamic Input Signal Range	10 mv to 10v, 60 db	

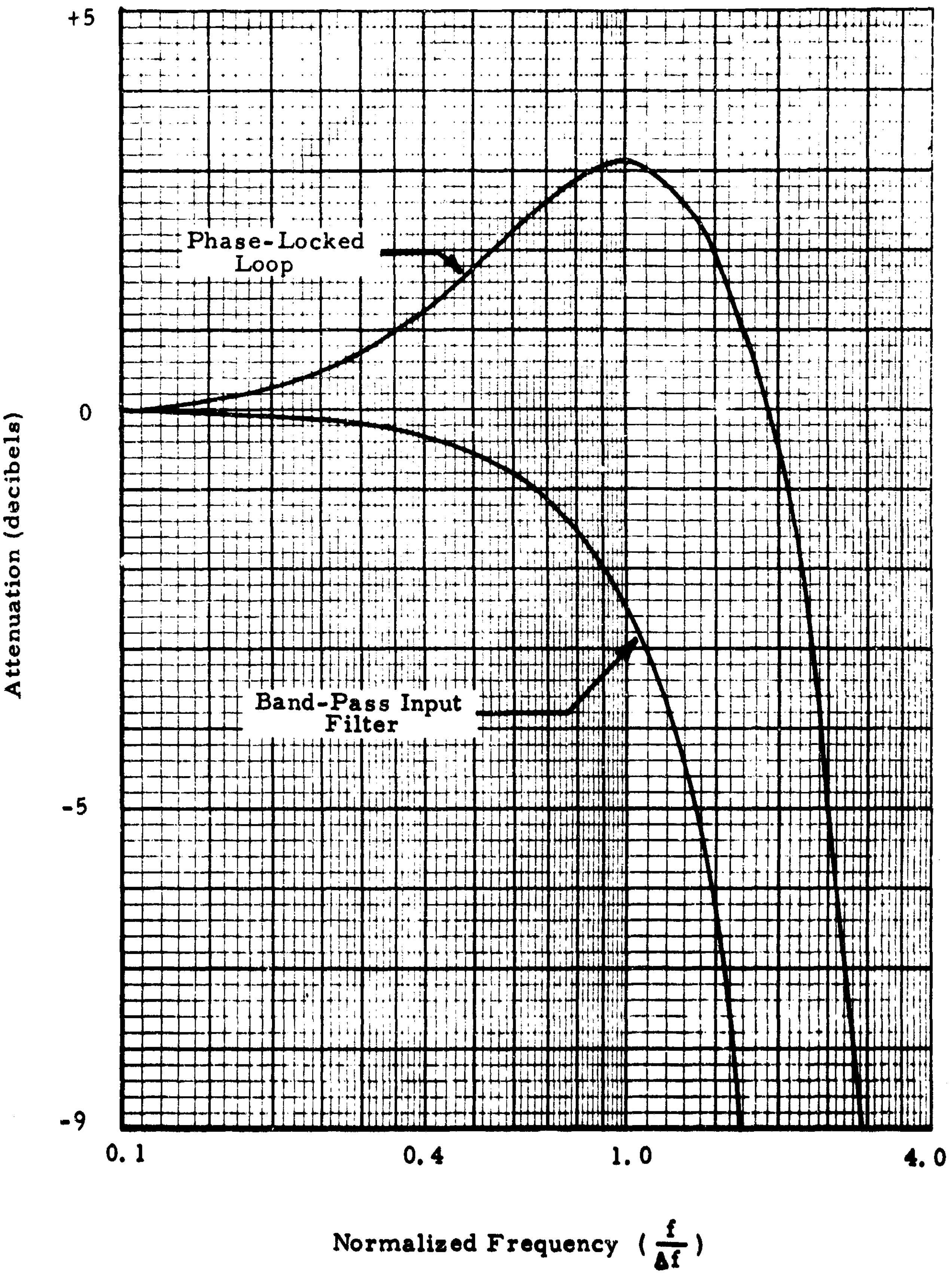


FIGURE I-2. 8-2
FREQUENCY RESPONSE CHARACTERISTICS OF
EMR MODEL 210 SUBCARRIER DISCRIMINATOR
PHASE-LOCKED LOOP AND BAND-PASS INPUT FILTER

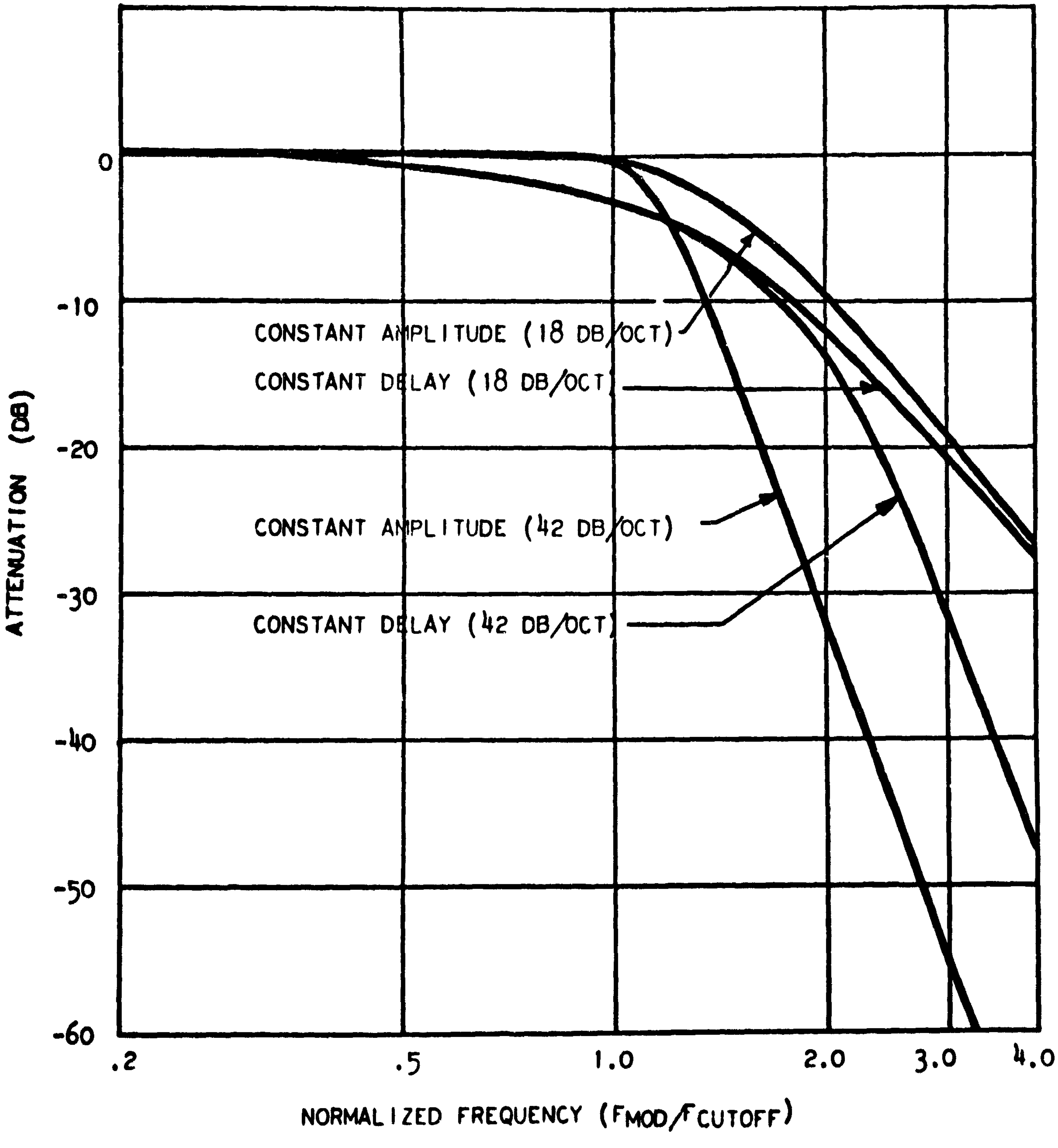


FIGURE I-2. 8-3
OUTPUT FILTER CHARACTERISTICS
EMR 210 SUBCARRIER DISCRIMINATOR

2.9 MAGNETIC TAPE RECORDER

2.9.1 General

A Minicom Model G-107 Tape Recorder and an Ampex Model FR 1400 Tape Recorder were evaluated to obtain amplitude response, phase response, noise distribution, intermodulation, signal-to-noise ratio, crosstalk, and total-harmonic-distortion data. Although the capabilities and design characteristics of the respective recorders are quite different, they were selected as representative of those presently being used or purchased for telemetry applications. The G-107 is a seven-track, one-half-inch recorder with frequency response to 300 kc at 60 ips; the FR 1400 is a fourteen-track one-inch recorder with response to 1.5 Mc at 120 ips. The objective of the tests was not a specification comparison among machines, but an analysis of the suitability of each recorder, as typical of similar machines, for use with the FM/FM expanded-proportional or constant-bandwidth baseband structures. Prior to the performance of any tests, manufacturer's representatives checked and aligned the machines to assure their proper operation.

2.9.2 Amplitude Response

Amplitude response measurements were made with each machine operating at 60 ips at normal record level using the procedure outlined in Section 2.9.1 of Volume II. Results of the amplitude response measurements are given in Figures I-2.9-1 and I-2.9-2. The frequency range of interest for the proposed, extended IRIG baseband is approximately 400 cps to 200 kc. As can be seen from the results, frequency response of either of the machines at 60 ips is adequate over this frequency range.

Unfortunately the two tape recorders which have been extensively evaluated were recalled by the manufacturers prior to the constant- and combinational-bandwidth baseband evaluation. An in-house Ampex FR 1400 with 500 kc electronics was used instead. This machine has been modified by the manufacturer to provide frequency responses to 600 kc at 120 ips. The frequency response is shown in Figure I-2.9-7.

2.9.3 Phase Response and Time Delay Variation

In order to preserve time correlation among channels and avoid creating harmonic distortion in each channel, the phase response of the tape recorder should be linear over the frequency range of the entire baseband as well as within the bandwidth of each channel. The phase response and time-delay variation of the tape recorders were measured using the technique outlined in Section 2.9.2 of Volume II. Results of the tests, summarized in Figure I-2.9-3, reveal the relative delay problems among channels introduced by tape recorders.

2.9.4 Noise Density

As a portion of the FM/FM telemetry link, a tape recorder is used to record and reproduce the baseband signal produced from the receiver through a mixer amplifier. Any noise coloration added by the tape recorder affects the subcarrier-to-noise ratio in each channel; therefore, noise level as a function of frequency was measured in both the G-107 and FR 1400 recorders. Results obtained for the two recorders are given in Figure I-2.9-4. Procedures used and the original data measured are contained in Volume II, Section 2.9.3.

2.9.5 Intermodulation Distortion

Intermodulation products generated by tape recorder nonlinearity, like similar products generated elsewhere in the system, affect baseband-noise levels. Intermodulation products also appear as distortion or noise on the data output of the affected channels. The level of the tape recorder sum and difference intermodulation frequencies were measured; the data are shown in Figure I-2.9-5. The original data and detailed procedure is included in Volume II, Section 2.9.4

2.9.6 Signal-to-Noise Ratio

Operating the tape recorders at normal record levels, the signal-to-noise ratio of the output was 27 db for the G-107 and 21 db for the RF 1400. These ratios are for normal sinewave record level, 1.0v rms, and open-circuit wideband noise. In both cases, the measurements are made with a true rms meter. When applying these ratios to a subcarfier multiplex, the individual subcarrier levels must be determined in relation to the total recorded multiplex level and only that noise in the subcarrier pass band considered to determine the subcarrier-to-noise ratio.

In comparing the signal-to-noise performance of the two machines, it should be remembered that the bandwidths are considerably different. If the noise were white (flat), the difference in bandwidths would result in 4 db difference in signal-to-noise ratio.

2.9.7 Total Harmonic Distortion

Total harmonic distortion as a function of frequency was measured on the Mincom Model G-107 and Ampex Model FR 1400 Recorders. Absolute measures of percentage distortion are a direct function of the adjustable sensitivity of the recorder input electronics and the level recorded on the tape. As such, a given percentage distortion has significance only as a function of frequency at a given recorder input level.

Total harmonic distortion was measured by recording the indicated frequency and level shown and searching the tape recorder output for harmonics with a frequency selective voltmeter. The harmonics measured were combined in rms fashion to obtain the rms total harmonic distortion. Harmonic distortion data on the G-107 and FR 1400 were taken at 1.0v rms input (normal record level) and are given in Figure I-2.9-6. Measured harmonic distortion increased slightly with frequency on both tape recorders in the general area of 40 kc and higher. Test procedures used and data obtained are in Section 2.9.5 of Volume II.

2.9.8 Crosstalk

Crosstalk between tracks was measured on each of the two recorders to determine if crosstalk increased in the frequency range to be occupied by higher frequency subcarriers. An input frequency at the normal record level of 1.0v rms was applied to each of the recorders and the output of the two tracks adjacent on the tape and to two tracks adjacent on the heads were measured. In the frequency range to 200 kc, no increase in crosstalk over that of the frequency range to 70 kc was measured on either machine. Original data and the procedures used are contained in Volume II, Section 2.9.6.

2.9.9 Tape Speed Error

Tape-speed-error tests were not performed on the tape recorders as part of the equipment evaluation program as it was felt more meaningful data would be obtained through a consideration of tape-recorder errors during the multiplex system tests. Neither of the machines was equipped with servo-speed control. Details of the multiplex systems tests regarding tape recorder errors are contained in Section 3.7 of this volume.

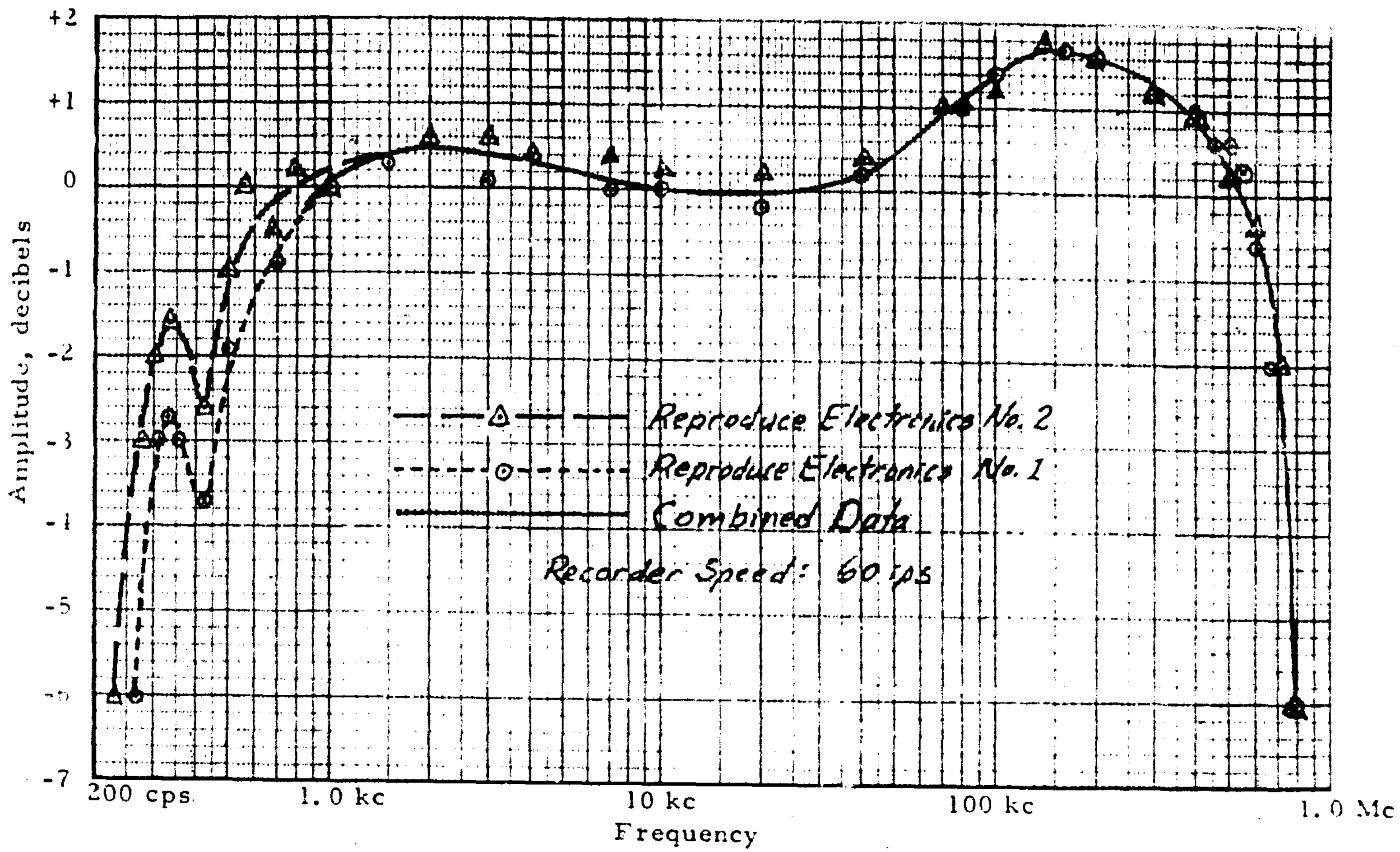


FIGURE I-2.9-1
FREQUENCY RESPONSE - AMPEX FR 1400

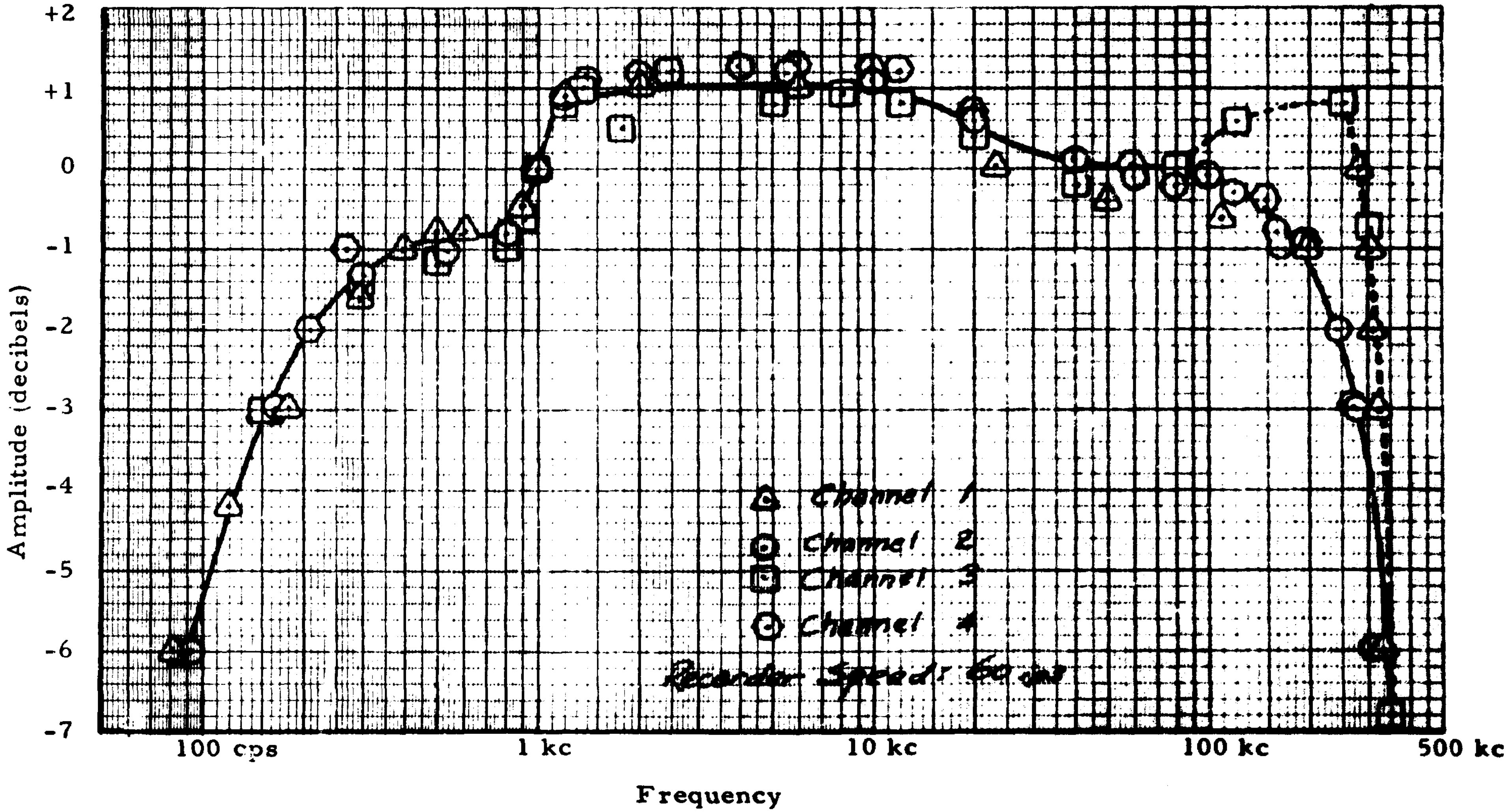
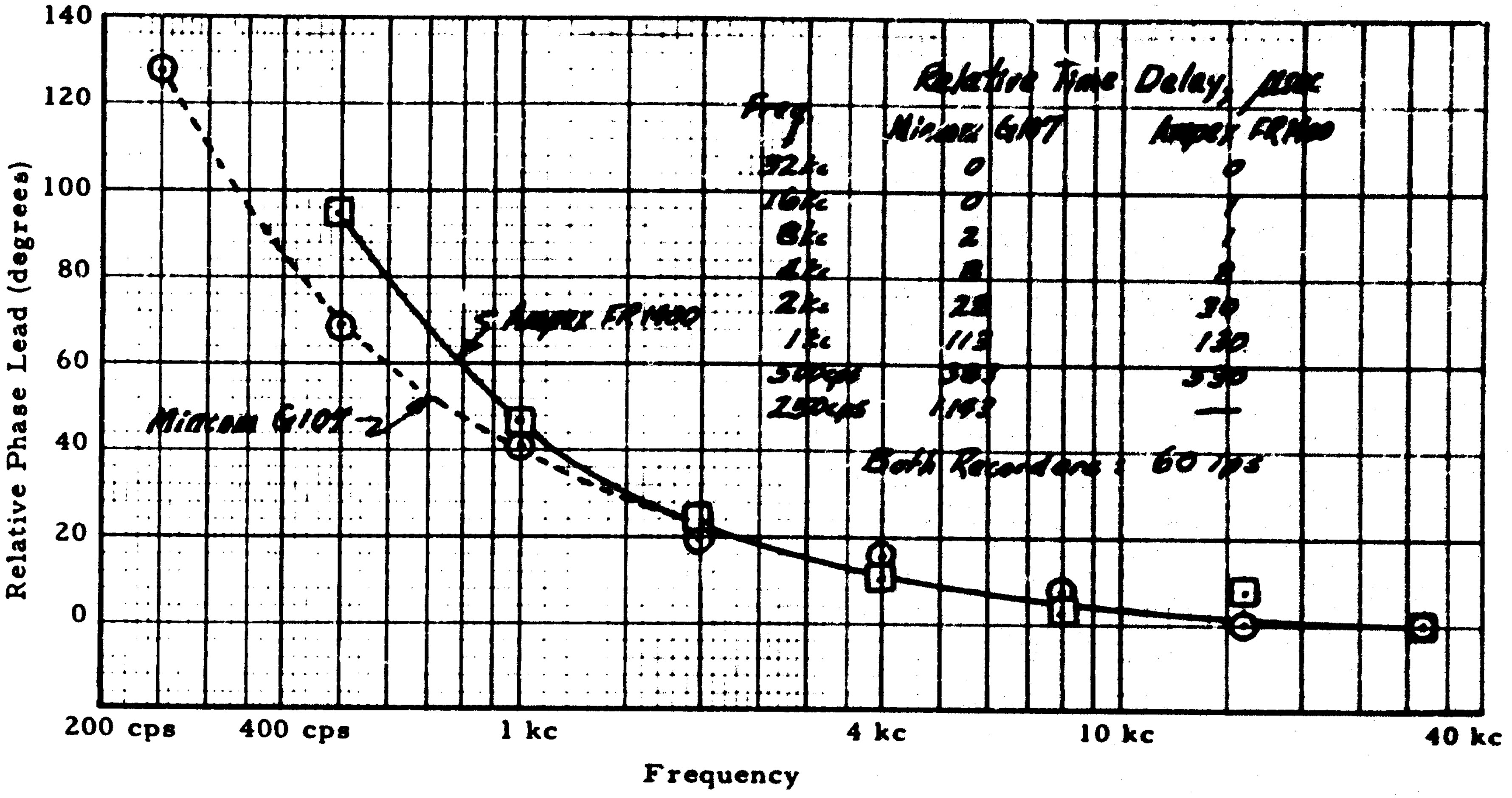


FIGURE I-2.9-2
FREQUENCY RESPONSE - MINCOM G-107



Relative Time Delay, µsec

Freq	Mincom G107	Ampex FR1400
32kc	0	0
16kc	0	1
8kc	2	1
4kc	8	8
2kc	28	30
1kc	113	130
500cps	383	330
250cps	1143	—

Both Recorders : 60 ips

FIGURE I-2. 9-3
TAPE RECORDER PHASE RESPONSE AND TIME DELAY CHARACTERISTICS

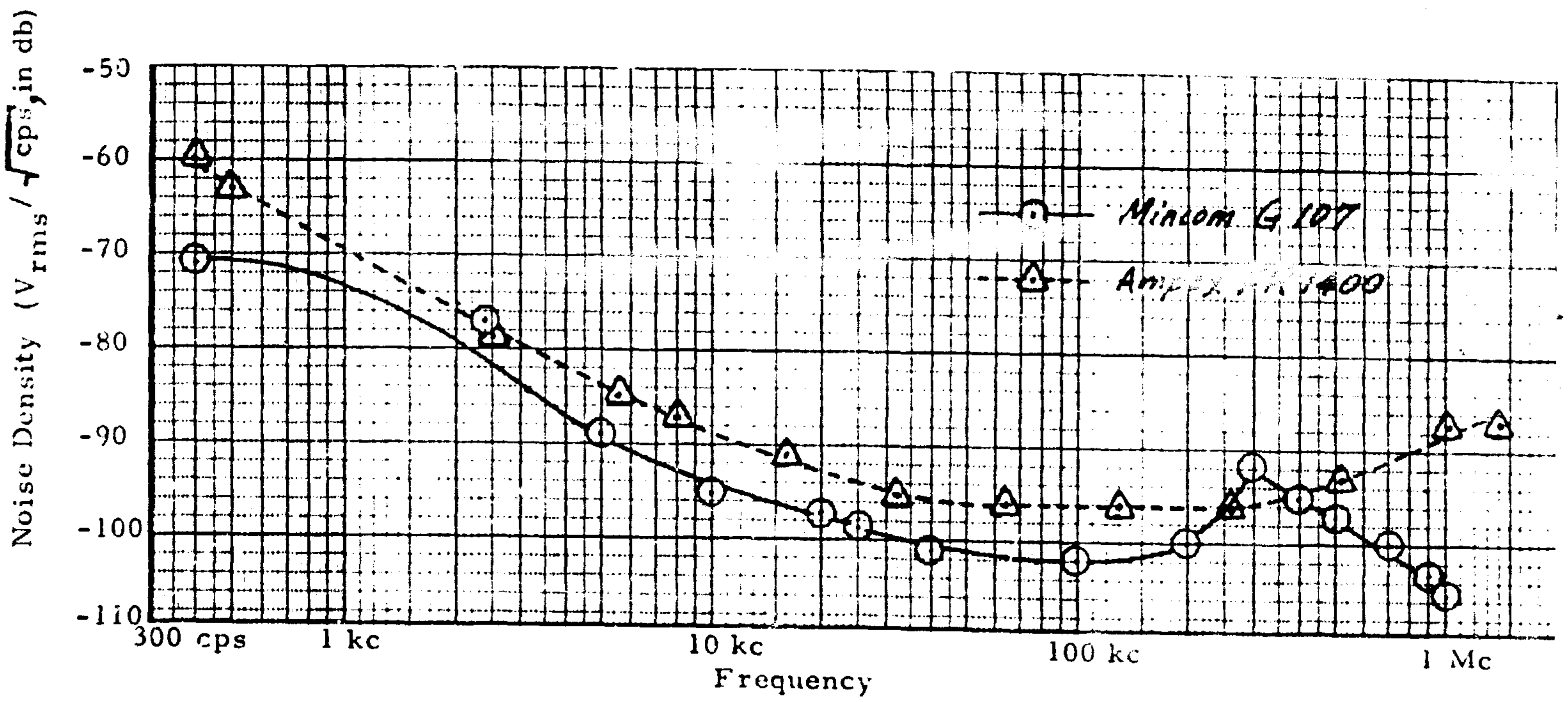


FIGURE I-2. 9-4
TAPE RECORDER NOISE DENSITY

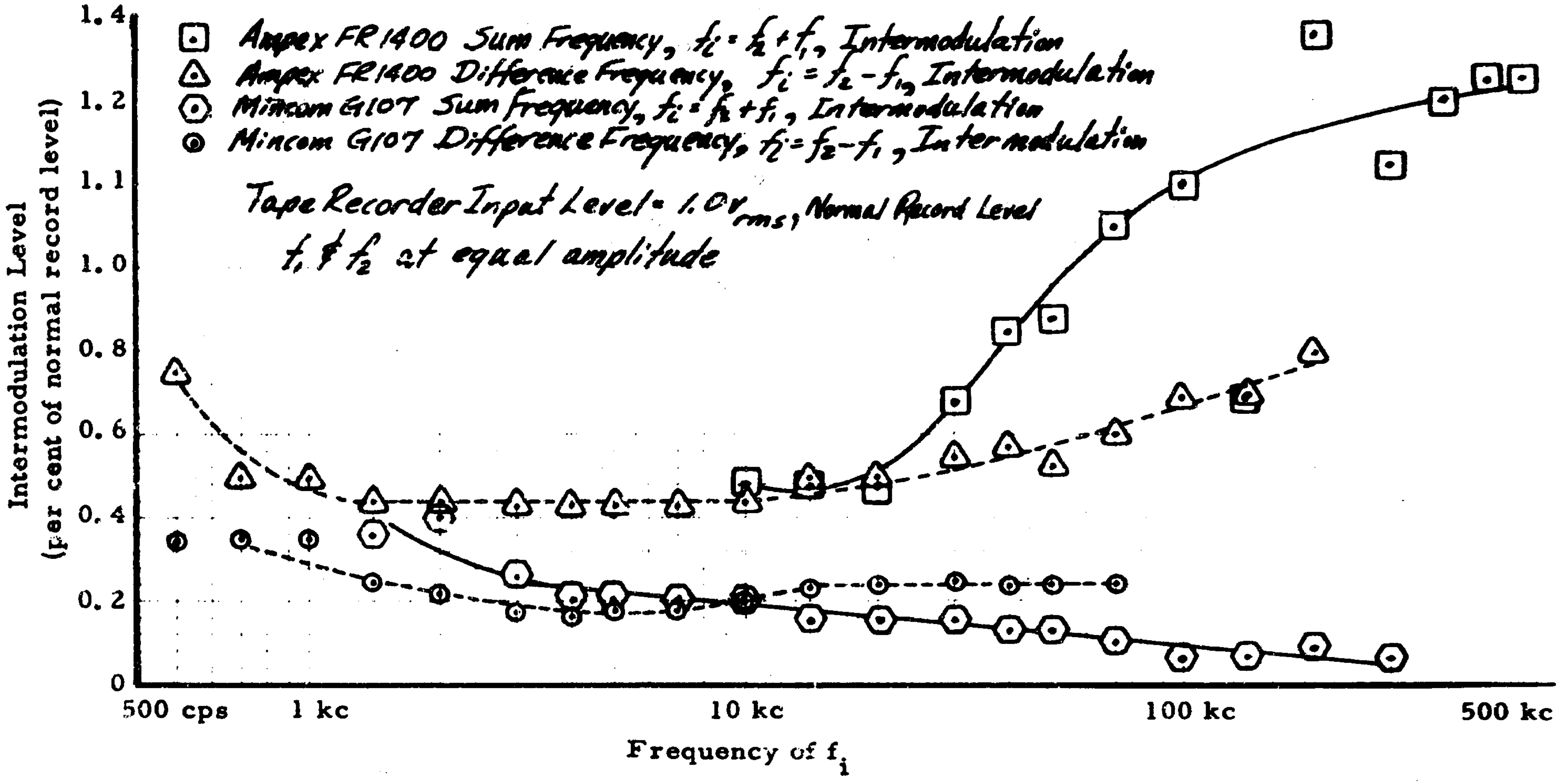


FIGURE I-2.9-5
TAPE RECORDER INTERMODULATION DISTORTION

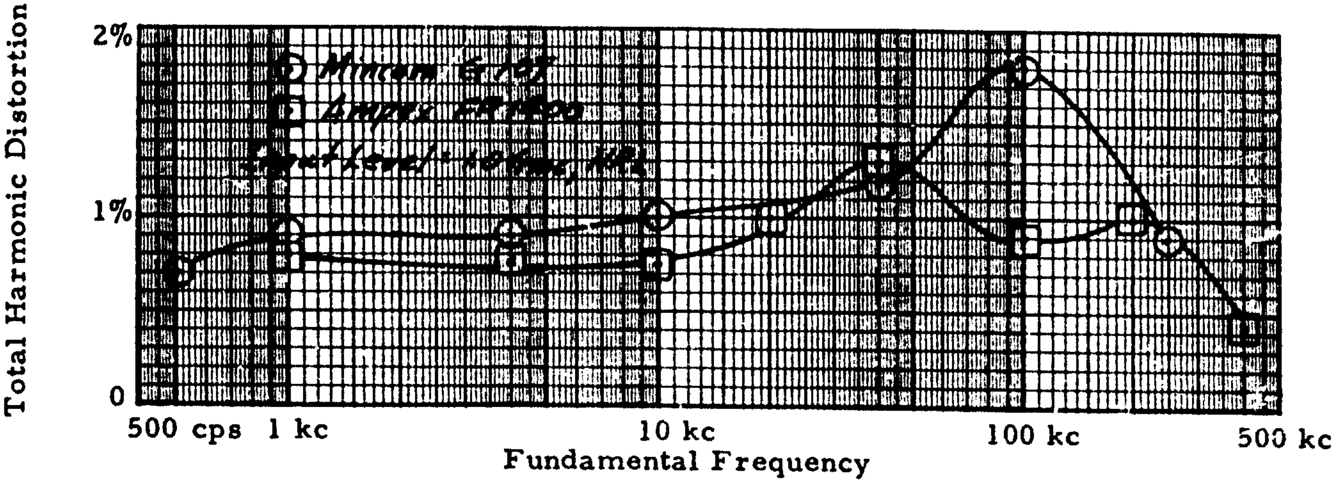


FIGURE I-2. 9-6
TAPE RECORDER TOTAL HARMONIC DISTORTION

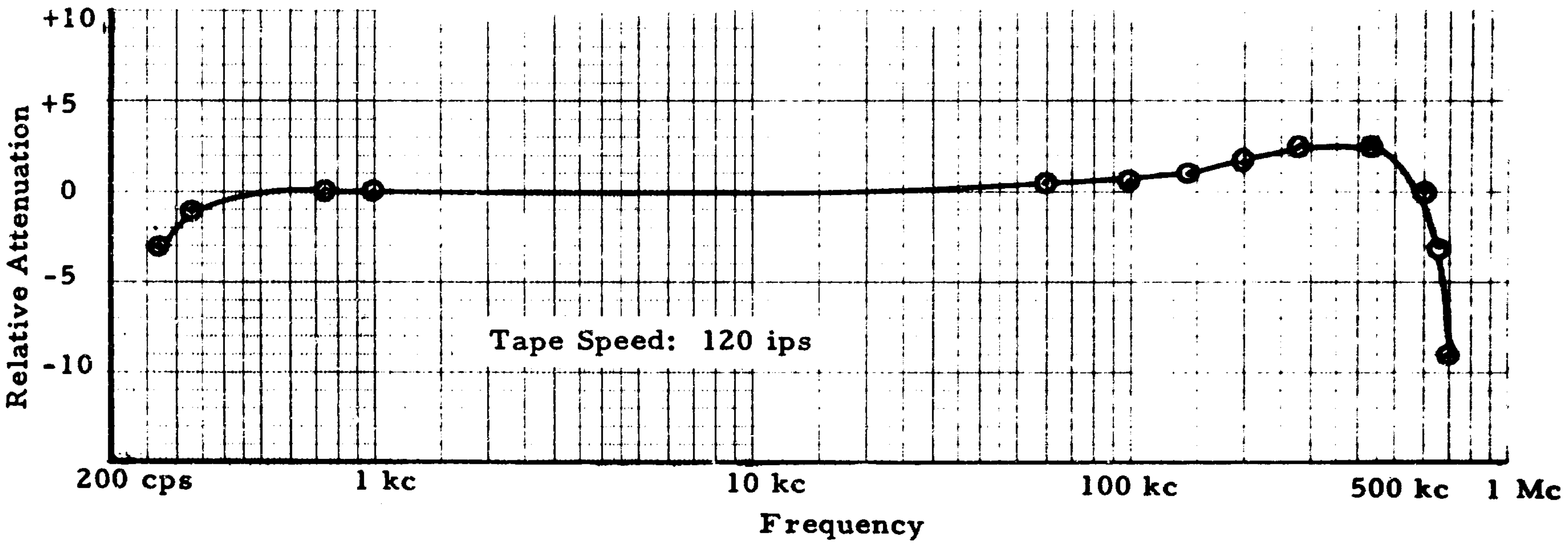


FIGURE I-2. 9-7
FREQUENCY RESPONSE - AMPEX - MODIFIED FR 1400

SECTION 3

SYSTEMS TEST

3.1 SYSTEM DESCRIPTION

A complete laboratory telemeter was constructed and used to experimentally evaluate each of the basebands. The equipment selected for use in the laboratory system was typical of that widely used in the field. It was evaluated in the equipment evaluation study and shown to be applicable for use in expanded FM/FM baseband applications.

The evaluation of each of the basebands consisted of specific system tests performed on either all the channels in the multiplex or on representative channels. The system tests began with experimental optimization of the pre-emphasis schedule and adjustment of the multiplex level to prevent the transmitter output from exceeding the radiated spectrum specification. Next, intermodulation, signal-to-noise, system error, and tape recorder tests were made. Finally, accuracy measurements were made for pulse modulation on those basebands containing a wideband (±15%) channel.

Each system test is described in detail in Section 3 of Volume II. The measured data is also included. The results of the system tests are summarized and discussed in the sections 3.2 through 3.8 of Volume I. Block diagrams and equipment used in the laboratory telemeter are discussed in the following three sections.

3.1.1 Proportional-Bandwidth Basebands

The block diagram of the laboratory telemeter used to evaluate the proportional-bandwidth basebands is shown in Figure I-3.1-1. The data source for each channel was a sine-wave oscillator, operated typically at a frequency equal to the nominal data cutoff frequency of the channel and producing a deviation ratio of 5. The voltage-controlled oscillators (VCOs) were combinations of Vector Model TS-41, Teledynamics Model 1270, and EMR Model 307A. The Sonex Model TEX 3210 Mixer Amplifier summed the VCO outputs and applied the multiplex to the transmitter. For pre-emphasis adjustments, the output level control of each affected VCO was used; the gain control on the mixer amplifier was used for adjustment of the total multiplex level.

The output of the Leach Model FM 200 Transmitter was attenuated with an RLC Electronic Model 101-30 Fixed Coaxial Attenuator followed by two General Radio Model 874-G10 Fixed Attenuators, and a Kay Electronic Model 30-0 Switchable Attenuator. The switchable attenuator was used to select the desired carrier-to-noise ratio for the receiver. The Nems-Clarke Model 1455A Receiver was operated with a 500-kc IF plug-in amplifier and a 1200-kc video filter. During signal-to-noise measurements at the IF output, the receiver AGC was externally held at a constant voltage.

For direct operation (without postdetection recording), the receiver output drove the EMR Model 210A Subcarrier Discriminators directly; however, for post-detection recording, the receiver output was de-emphasized by the EMR Model 264A Mixer Amplifier, and a reference tone from the EMR 226A Reference Oscillator was added to the multiplex. A MINCOM Model G107 Tape Recorder was used in the proportional-bandwidth baseband evaluation. On playback the reference tone was demodulated by the reference discriminator and used for tape-speed compensation. The multiplex was delayed by an amount equal to the delay inherent in the reference discriminator before driving the bank of subcarrier discriminators. Appropriate EMR Model 210B-01 Channel Selectors and EMR Model 210C-01 Low-Pass Output Filters were plugged into the discriminators to demodulate the subcarriers.

3.1.2 Constant-Bandwidth Basebands

The block diagram of the airborne portion of the laboratory telemeter used to evaluate the constant-bandwidth baseband is shown in Figure I-3.1-2, and the ground portion of the telemeter is shown in Figure I-3.1-3. The data sources were, again, sine-wave oscillators operating normally at 1000 cps, which is the nominal cutoff frequency for operation at a deviation ratio of 2. Since all the data sources typically operate at the same frequency, separate sources were not used. The VCOs were all EMR Model 307As with full bandwidth deviation of ±2 kc. The EMR Model 316X translated the VCOs in groups of five to the higher frequency positions in the baseband. The group A Model 316A did not translate the first six channels, but delayed the group an amount equal to the delay of the other Model 316X Translators. The EMR Model 311A summed the VCO outputs to form the multiplex which then deviated the transmitter. For pre-emphasis adjustments, the output level control of each VCO in a particular group was used. The relative level of each group was then adjusted with the output level control on the Model 316. The total multiplex level could then be adjusted with the Model 311A output level control. The rf link was identical to that used for the proportional-bandwidth basebands.

The receiver output was de-emphasized in a line-drive amplifier and the 240-kc reference tone was added to the multiplex. For constant-bandwidth systems the reference tone was used both for tape-speed compensation and for synthesis of the detranslation frequencies. The de-emphasized multiplex could then be recorded or connected directly into the remainder of the system. The tape recorder used in the constant-bandwidth baseband evaluation was a modified Ampex FR 1400 (described in detail in section 2.9). The output of the tape recorder or receiver was applied to the EMR Model 259A Detranslator and to the reference discriminator. The EMR Model 260 Calibrator is shown in Figure I-3.1-3 to illustrate a typical ground station, but was not used in the laboratory telemeter. The reference tone was extracted by the EMR Model 210T-02 Channel Selector and used to generate the detranslation frequencies in the Model 259A. The Model

259A output could be selected to provide the desired subcarrier group output for demodulation. The discriminator bank was identical to the system for proportional-bandwidth with the exception of the plug-in channel selectors and low-pass output filters.

3.1.3 Combinational-Bandwidth Baseband

The laboratory telemeter for the combinational-bandwidth baseband evaluation was identical to that for the constant-bandwidth telemeter with the addition of the first 11 IRIG channels from the proportional-bandwidth telemeter. The IRIG channels from the Model TEX 3210 Mixer formed a fifth group input to the Model 311A Mixer as shown by the dashed lines in Figure I-3.1-2.

The ground portion of the telemeter was exactly identical to that shown in Figure I-3.1-3 and used for the constant-bandwidth baseband evaluation. For demodulation of the IRIG subcarriers, the Model 259A was operated in the Group A position, which is the nontranslated group, and appropriate channel selectors and low-pass output filters were used in the Model 210 Discriminators. Additional discriminators could also be used.

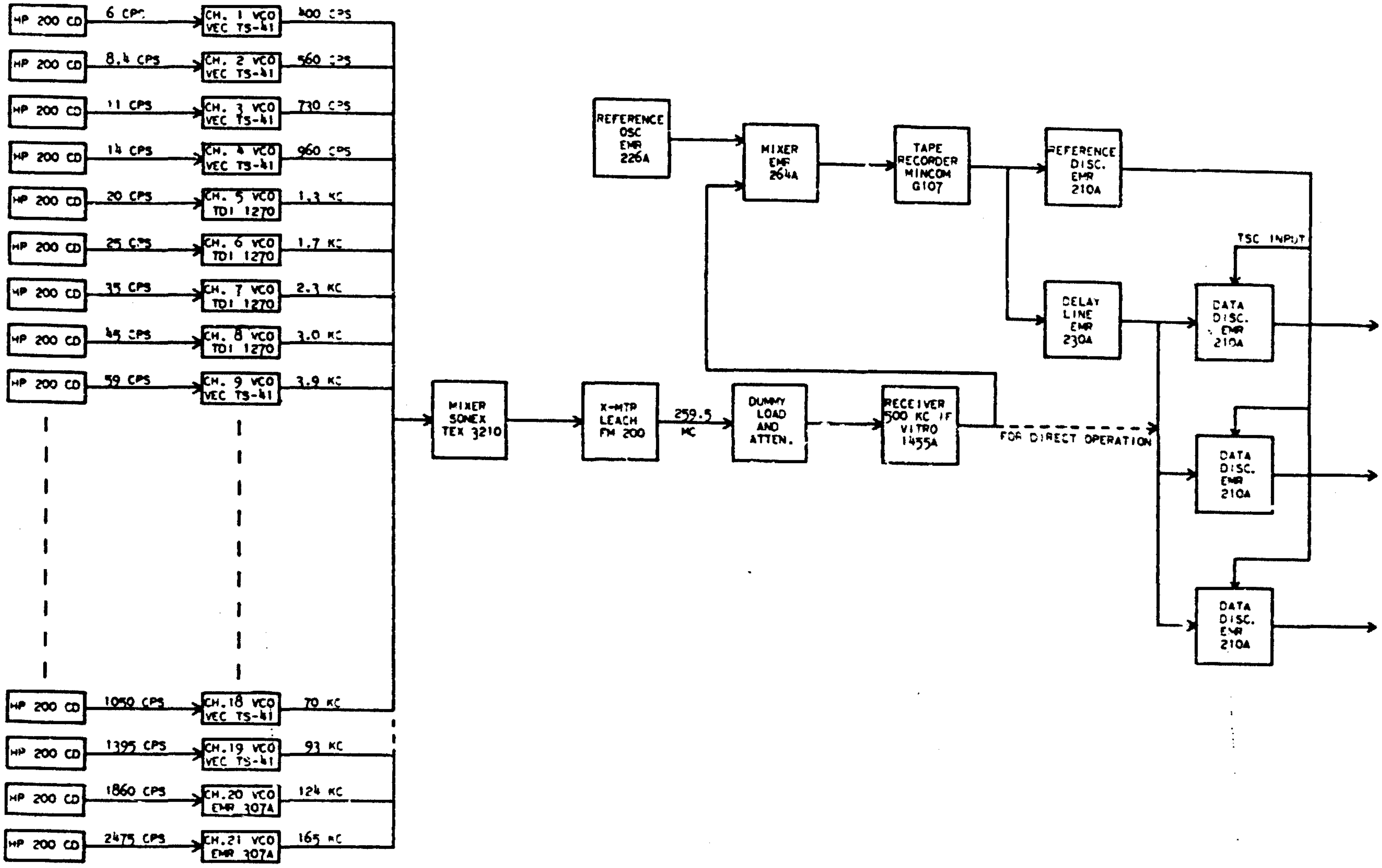


FIGURE I-3.1-1
BLOCK DIAGRAM OF LABORATORY TELEMETER USED FOR EVALUATION OF PROPORTIONAL BANDWIDTH BASEBANDS

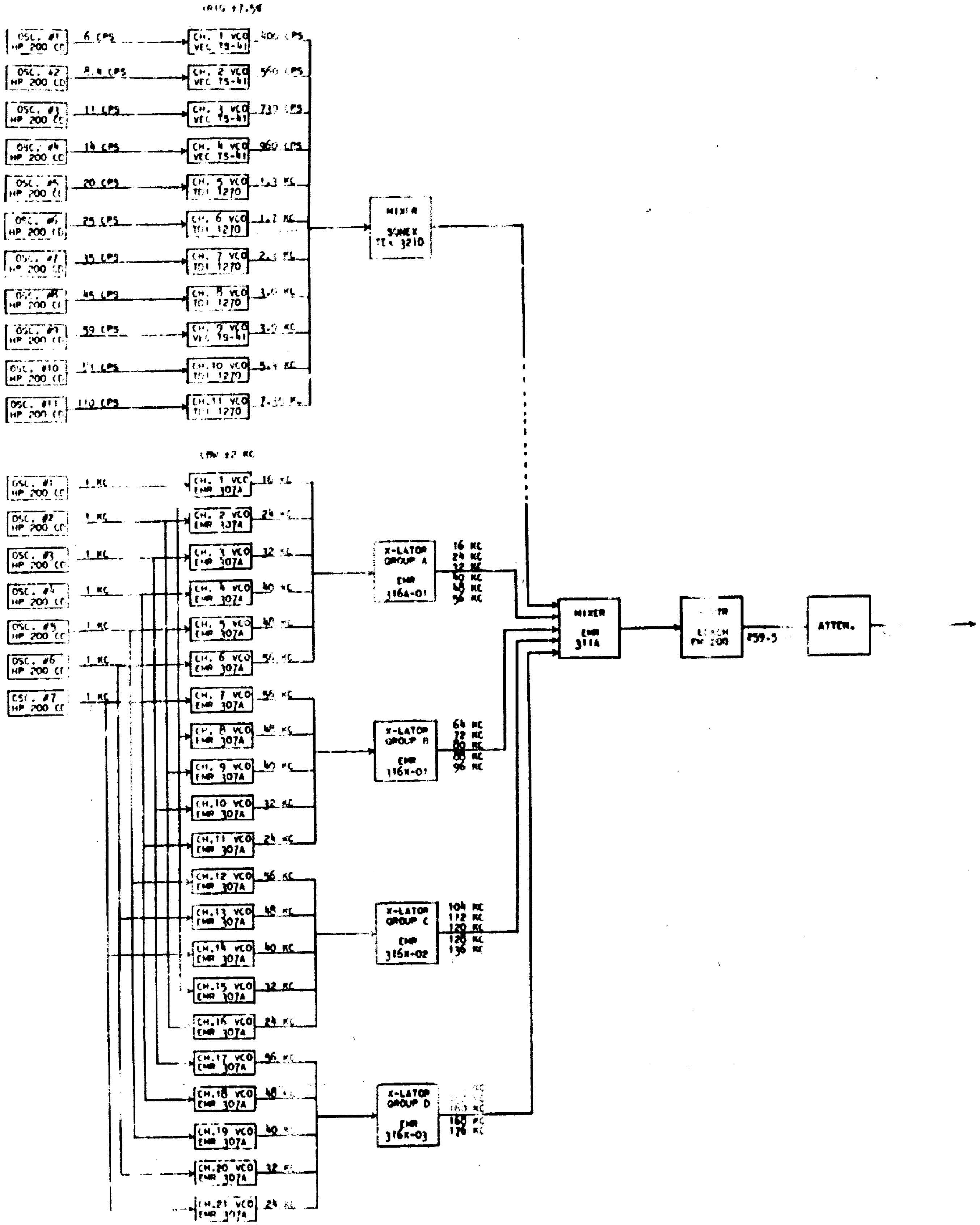


FIGURE I-3. 1-2
BLOCK DIAGRAM OF AIRBORNE LABORATORY TELEMETER
USED FOR EVALUATION OF CONSTANT AND
COMBINATIONAL BANDWIDTH BASEBANDS

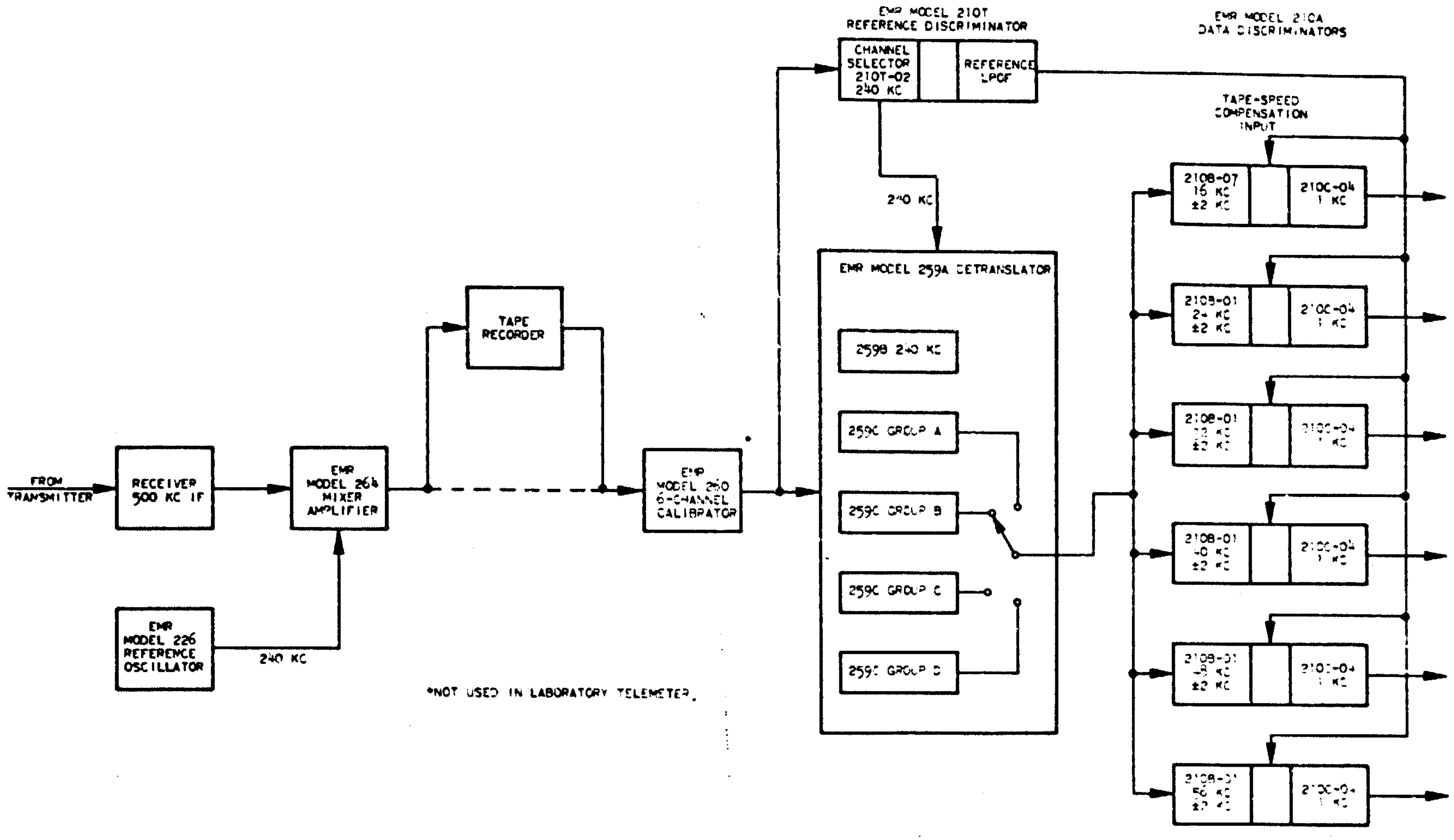


FIGURE I-3.1-3
BLOCK DIAGRAM OF GROUND LABORATORY TELEMETER USED FOR EVALUATION OF CONSTANT AND COMBINATIONAL BANDWIDTH BASEBANDS

3.2 PRE-EMPHASIS

3.2.1 General

For each baseband considered, the pre-emphasis was optimized to provide each channel in the multiplex with equal signal-to-noise performance when the receiver was operated at threshold. In addition, the multiplex levels were adjusted to deviate the transmitter so that the radiated spectrum did not exceed a specified limit.

In optimizing the pre-emphasis, the receiver was operated at an IF carrier-to-noise ratio of 9 db, which is approximately the receiver threshold. Next, the individual unmodulated VCO outputs were adjusted to produce identical subcarrier-to-noise ratios as measured at the output of the band-pass input filter of the subcarrier discriminator. Ideally, when a pre-emphasis schedule is optimized, the signal-to-noise ratio is measured at the subcarrier discriminator output; however, this measurement is difficult to make, especially on the low-frequency channels when the system is operating near threshold. Therefore, it is assumed that if all the subcarrier discriminators have identical input signal-to-noise ratios and identical deviation ratios, their output signal-to-noise ratios will be identical.

Although transmitter incidental FM was not a problem under the laboratory conditions of this evaluation, a minimum peak transmitter deviation of approximately 3 kc for each channel was used. This minimum allowable deviation of the lower-frequency channels provided an increased subcarrier-to-noise ratio to minimize the effect of incidental FM or other low-frequency noise present (e.g., intermodulation products from the high-frequency channels). Increased low-frequency channel deviation costs very little for a typically pre-emphasized multiplex since the rms transmitter deviation is essentially determined by the four or five highest-frequency channels, which are operated at high amplitude.

3.2.2 Proportional-Bandwidth Basebands

The experimental pre-emphasis schedules for the proportional-bandwidth basebands are summarized in Table I-3.2-1 and are displayed graphically in Figures I-3.2-2 through I-3.2-6. These figures show the relative level of each VCO in the multiplex, as well as the subcarrier-to-noise ratio that was obtained with the receiver operated at a carrier-to-noise ratio of 9 db.

A significant characteristic of the pre-emphasis schedules for the IRIG multiplexes, Figures I-3.2-2 and I-3.2-3, is the absence of the theoretical 3/2 power taper (9 db per octave). The experimental tapers are approximately linear (6 db per octave); however, with the expansion of the baseband to include the higher frequency channels, the tapers approach the theoretical slope. This departure from theoretical is caused by the shape of the receiver output noise density and the frequency-dependent nature of the transmitter deviation sensitivity above 70 kc. As shown in Figure I-2.6-3, the slope of the receiver noise-density curve for a carrier-to-noise ratio of 9 db is flat to 10 kc, reaches 6 db per octave at 50 kc, and rolls off above 200 kc. For a proportional-bandwidth system, the subcarrier bandwidths increase with center frequency at the rate of 3 db per octave; therefore, the slope of the pre-emphasis curve should reach 9 db per octave for channels with center frequencies near 50 kc. Then the slope should decrease for channels above 100 kc. This characteristic would occur if it were not for the rolloff of the transmitter-deviation sensitivity.

As shown in Figure I-2.5-6, the transmitter-deviation sensitivity is constant to 70 kc and then begins to fall off. The reduced deviation sensitivity necessitates increased VCO levels to maintain the desired transmitter deviation. The effects of receiver-noise density and transmitter-deviation sensitivity thus cause the experimental pre-emphasis schedule to depart from the theoretical 3/2 power taper for the basebands with center frequencies below 70 kc, and cause the basebands with higher center frequencies to approach the theoretical curve.

The two additional channels at 93 kc and 124 kc allowed by the initial analysis described in section 1.5 were added to the multiplex, the transmitter input adjusted to 1.0v rms (based on the gaussian results obtained for the IRIG baseband discussed in section 3.3, the following section), and the pre-emphasis optimized. Results are shown in Figure I-3.2-4. The pre-emphasis was optimized at a carrier-to-noise ratio of 9 db, receiver threshold. A check of the radiated spectrum specification indicated that the 1.0v rms transmitter input level caused excessive radiated energy. A decrease of the transmitter input level to 0.9v rms provided a marked decrease in radiated spectrum to slightly above specification; however, this decreased the subcarrier-to-noise ratio only 1 db (to approximately 14 db).

Since the subcarriers were still well above their threshold, another channel was added at 165 kc. The pre-emphasis schedule and subcarrier-to-noise performance at receiver threshold are shown in Figure I-3.2-5. For this multiplex, the channels above 10.5 kc were pre-emphasized and provided subcarrier-to-noise ratios of 10 db, slightly above threshold. The channels at 10.5 kc and below were limited to 3 kc minimum deviation; therefore, they produced higher subcarrier-to-noise ratios.

3.2.3 Constant- and Combinational-Bandwidth Basebands

The pre-emphasis schedules for the constant- and combinational-bandwidth basebands were optimized using the same procedure as described for the proportional-bandwidth basebands. In the combinational-bandwidth baseband multiplex, the pre-emphasis schedule for the 11 IRIG channels was identical to that used for the IRIG 18-channel baseband, and the pre-emphasis for the constant-bandwidth channels was identical to the schedule used for the constant-bandwidth baseband. The experimental pre-emphasis schedules for the constant- and combinational-bandwidth basebands are summarized in Table I-3.2-7 and are displayed graphically in Figures I-3.2-8 and I-3.2-9. In all cases, the multiplex levels were adjusted to deviate the transmitter so that the radiated spectrum did not exceed specifications.

The five higher-frequency channels, 17 through 21, Group D, of the constant-bandwidth baseband were removed and the transmitter input level readjusted to the maximum allowed by the radiated-spectrum specification. With a receiver carrier-to-noise ratio, $(S/N)_c$, of 9 db, the subcarrier-to-noise ratios, $(S/N)_s$, measured for channel 14, 120.0 kc, increased to 11.3 db; for channel 10, 88.0 kc, it increased to 12.3 db; and for channel 6, 56.0 kc, it increased to 12.0 db. This performance should be compared with the constant-bandwidth 21-channel baseband, Figure I-3.2-8, which exhibited subcarrier-to-noise ratios between 5 and 6 db. As both the 16-channel and 21-channel constant-bandwidth basebands could not be evaluated, the trade of 6 db subcarrier-to-noise performance for five additional channels seemed worthwhile, and the 21-channel system was evaluated.

Note that the subcarrier-to-noise performance of the IRIG channels in the combinational baseband is superior to that of the constant-bandwidth channels. By experiment, it was found that the relative levels of the two groups of channels, IRIG and constant bandwidth, had little effect on the signal-to-noise performance of the constant-bandwidth channels. Thus, the IRIG channels were added at a level approximately equal to that level at which they would normally be used in a full IRIG multiplex. There are numerous choices as to how to operate the two groups; however, the choice made gives excellent performance of the IRIG channels without deteriorating the performance of the constant-bandwidth channels. The addition of the IRIG channels actually enhances the performance of the constant-bandwidth channels by spreading the radiated spectrum and allowing increased transmitter deviation under the same spectrum specification. This is discussed in more detail in section 3.3 of this volume.

The shape of the pre-emphasis curves for the constant-bandwidth channels follow very closely the shape of the receiver output noise-density curves shown in Figure I-2.6-3, since the subcarrier bandwidths do not increase with center frequency. Again, however, the transmitter-deviation sensitivity must also be taken into account on the high-frequency channels. Using the noise-density curves shown in Figure I-2.6-3, the channel performance can easily be predicted for carrier-to-noise ratios other than that at which the pre-emphasis has been optimized. In addition, such noise-density measurements can be of field use when setting pre-emphasis schedules.

The technique described thus far for setting system pre-emphasis has only established the relative levels of the individual channels. The absolute level (i.e., the actual transmitter deviation allotted to each channel) depends upon the total allowable transmitter deviation. In the past, the total transmitter deviation has been fixed at ±125 kc peak deviation; however, for this evaluation the transmitter radiated spectrum was fixed at a specified level. Limiting the radiated spectrum has the effect of limiting the total rms multiplex level, and thereby establishes the allowable transmitter deviation allotted to each channel. Further discussion of the radiated spectrum is contained in the next section. The total optimization procedure is thus one of adjusting individual VCO levels while maintaining a constant total-rms multiplex level. Fortunately, the four or five higher-frequency channels dominate the total rms level, and the optimization procedure converges fairly rapidly. The detailed procedure, measured data, and a technique for finding an initial trial deviation for the highest frequency in a multiplex are contained in Volume II, section 3.1.

TABLE I-3.2-1
SUMMARY OF PRE-EMPHASIS SCHEDULES FOR PROPORTIONAL BANDWIDTH BASEBANDS

		Peak Transmitter Deviation Allotted To Each Subcarrier Channel			
Channel		IRIG 1 - 18 (kc)	IRIG 1 - 16 and E (kc)	Expanded 1 - 21 (kc)	Expanded 1 - 19 and H (kc)
No.	Frequency (kc)				
1	0.40 ±7.5%	4.56	3.71	2.89	2.42
2	0.56 ±7.5%	4.56	3.60	2.89	2.77
3	0.73 ±7.5%	4.56	3.82	3.07	2.50
4	0.96 ±7.5%	4.56	3.70	2.89	2.62
5	1.30 ±7.5%	4.56	3.82	3.07	2.67
6	1.70 ±7.5%	5.51	4.24	2.89	2.42
7	2.30 ±7.5%	6.15	4.77	3.07	2.77
8	3.00 ±7.5%	7.00	5.30	2.89	2.42
9	3.90 ±7.5%	7.74	6.05	2.89	2.67
10	5.40 ±7.5%	9.75	7.74	2.84	2.54
11	7.35 ±7.5%	12.2	9.22	2.88	2.62
12	10.5 ±7.5%	15.7	11.7	3.01	2.55
13	14.5 ±7.5%	19.1	14.4	3.18	2.70
14	22.0 ±7.5%	26.5	20.2	4.66	2.69
15	30.0 ±7.5%	33.9	28.4	5.93	3.44
16	40.0 ±7.5%	42.4	35.6	8.00	4.76
17	52.5 ±7.5%	50.9	--	10.8	7.2
18	70.0 ±7.5%	63.6	--	15.1	10.8
19	93.0 ±7.5%	--	--	22.8	15.9
20	124.0 ±7.5%	--	--	37.6	--
21	165.0 ±7.5%	--	--	60.9	--
E	70.0 ±15%	--	90.0	--	--
H	165.0 ±15%	--	--	--	62.5

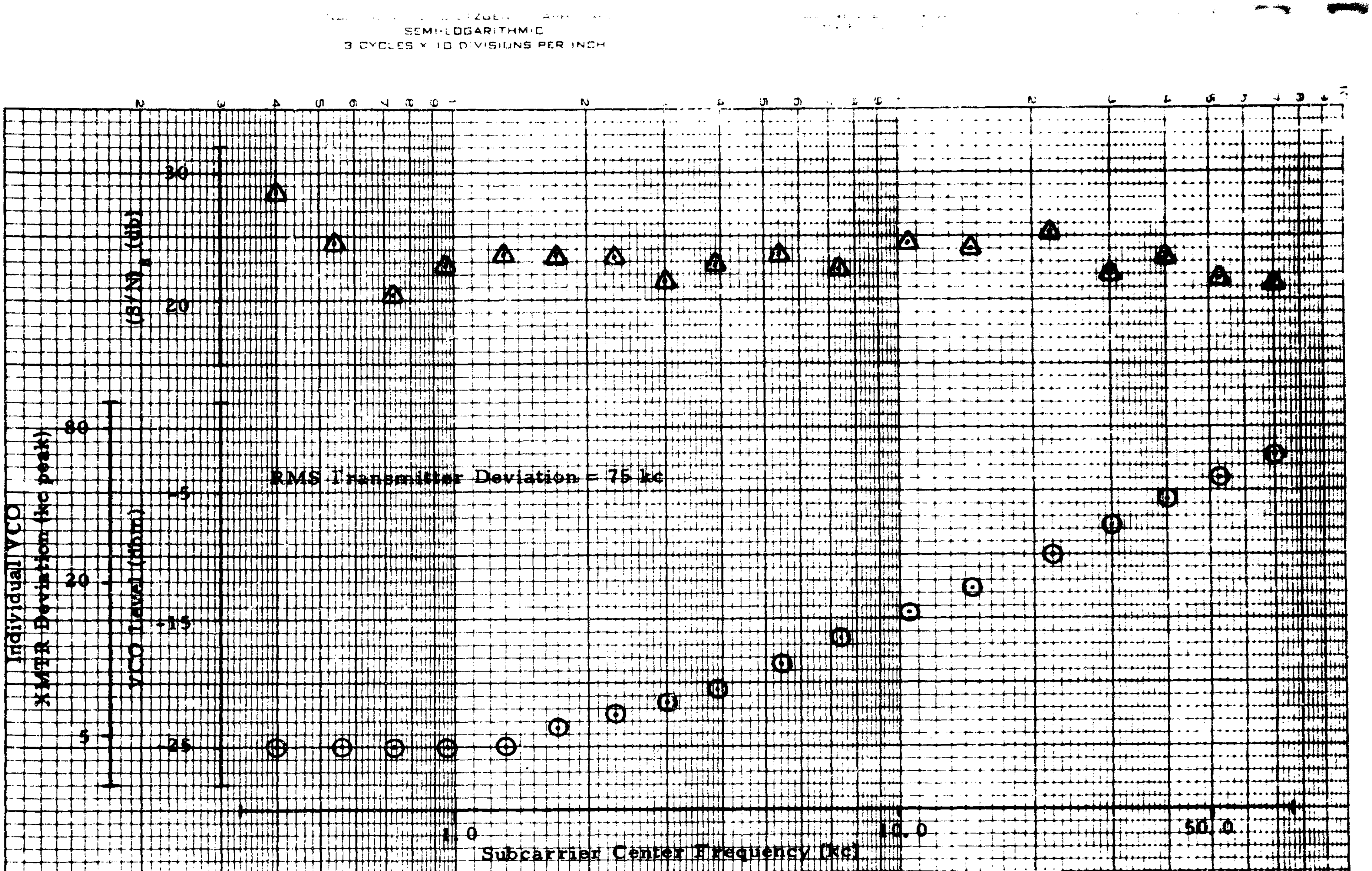


FIGURE I-3.2-2
PRE-EMPHASIS SCHEDULE FOR IRIG PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 THROUGH 18

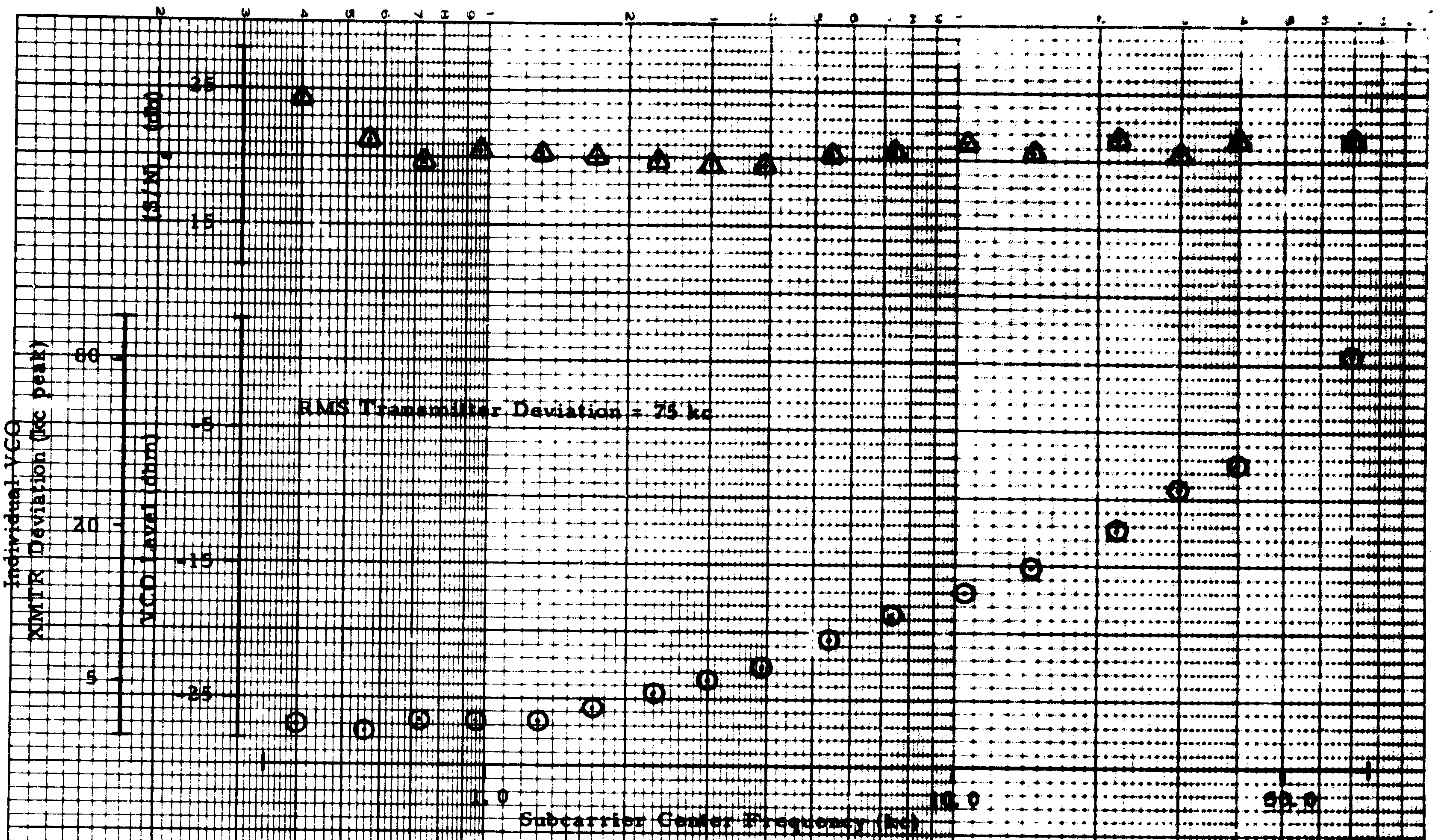


FIGURE I-3. 2-3
PRE-EMPHASIS SCHEDULE FOR IRIG PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 THROUGH 16 AND E

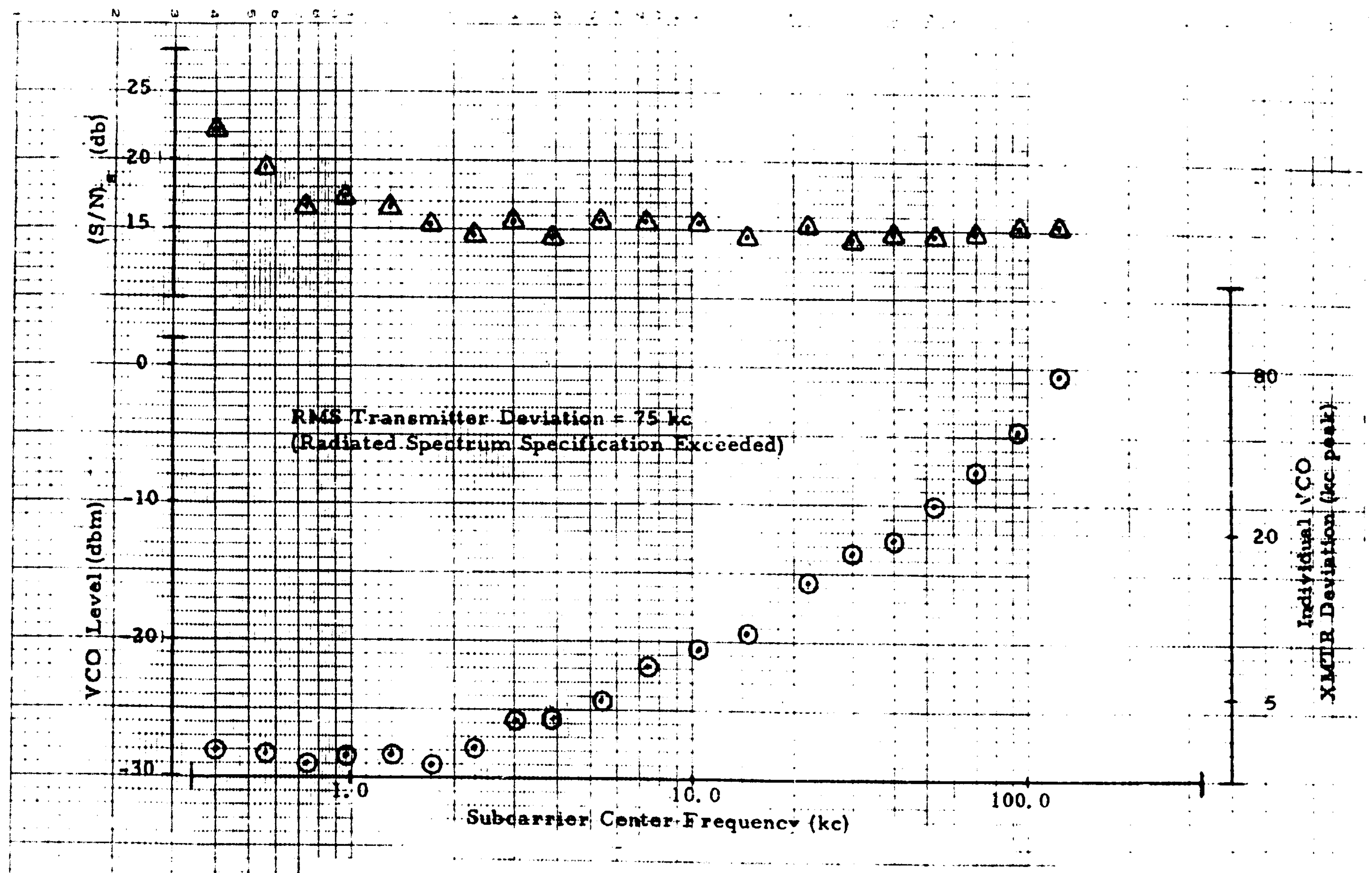


FIGURE I-3.2-4
PRE-EMPHASIS SCHEDULE FOR EXPANDED PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 THROUGH 20

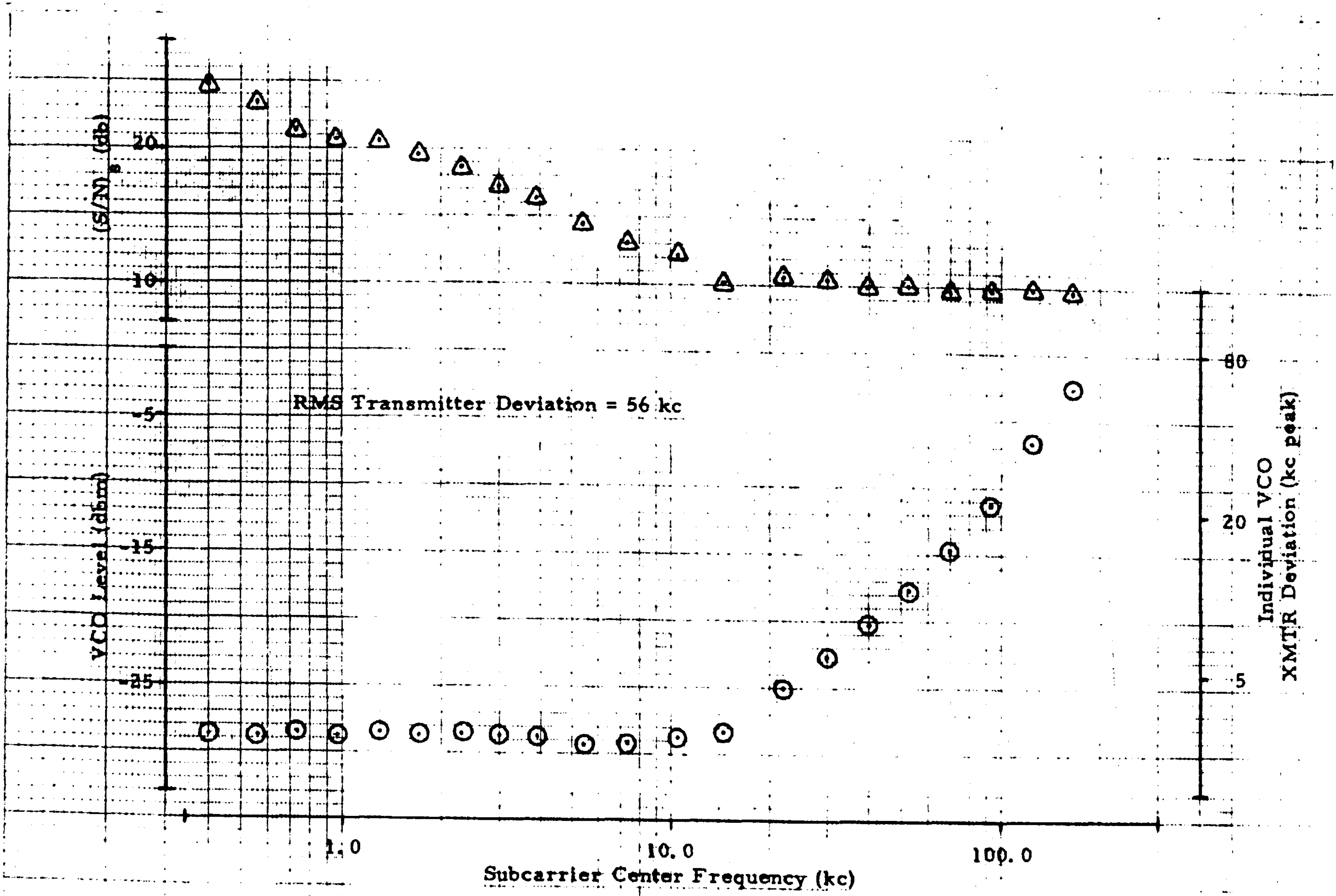


FIGURE I-3.2-5
PRE-EMPHASIS SCHEDULE FOR EXPANDED PROPORTIONAL
BANDWIDTH MULTIPLEX, CHANNELS 1 - 21

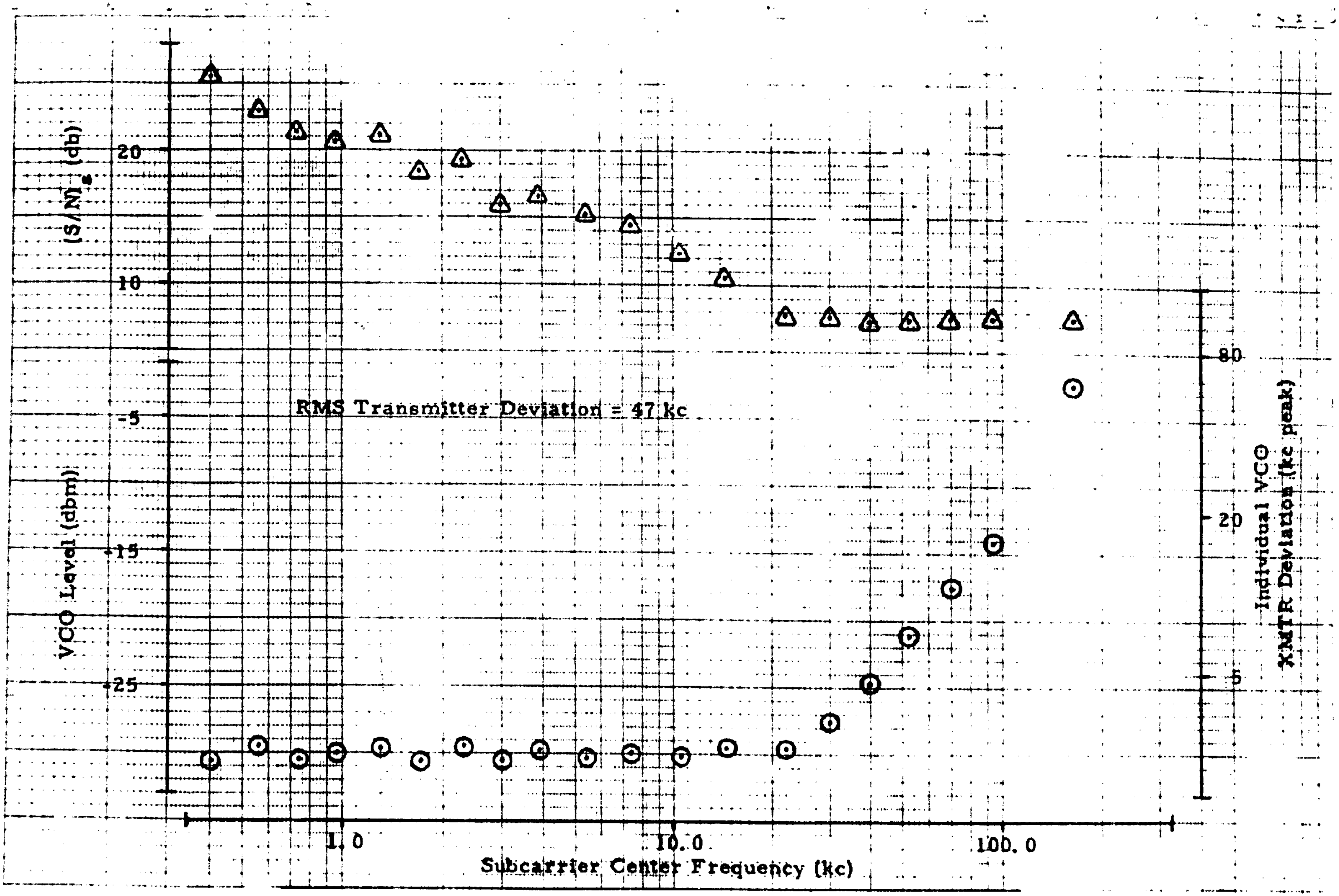


FIGURE I-3.2-6
PRE-EMPHASIS SCHEDULE FOR EXPANDED PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 - 19 AND H

TABLE I-3. 2-7

SUMMARY OF PRE-EMPHASIS SCHEDULES FOR CONSTANT AND COMBINATIONAL BANDWIDTH BASEBANDS

Channel		Peak Transmitter Deviation Allotted to Each Subcarrier Channel (kc)	
No.	Frequency (kc)	Constant Bandwidth Multiplex	Combinational Bandwidth Multiplex
21	176. 0 ±2 kc	14. 52	24. 42
20	168. 0 ±2 kc	13. 71	23. 05
19	160. 0 ±2 kc	13. 09	22. 01
18	152. 0 ±2 kc	12. 21	20. 78
17	144. 0 ±2 kc	11. 01	18. 72
16	136. 0 ±2 kc	10. 15	17. 07
15	128. 0 ±2 kc	9. 15	15. 39
14	120. 0 ±2 kc	8. 63	14. 86
13	112. 0 ±2 kc	7. 87	13. 55
12	104. 0 ±2 kc	7. 01	12. 21
11	96. 0 ±2 kc	6. 39	11. 01
10	88. 0 ±2 kc	5. 83	10. 03
9	80. 0 ±2 kc	5. 44	9. 36
8	72. 0 ±2 kc	4. 96	8. 54
7	64. 0 ±2 kc	4. 52	7. 69
6	56. 0 ±2 kc	3. 80	6. 47
5	48. 0 ±2 kc	3. 39	5. 76
4	40. 0 ±2 kc	3. 02	5. 13
3	32. 0 ±2 kc	2. 42	4. 17
2	24. 0 ±2 kc	2. 40	4. 08
1	16. 0 ±2 kc	2. 13	3. 63
11	7. 35 ±7. 5%		12. 07
10	5. 40 ±7. 5%		9. 69
9	3. 90 ±7. 5%		7. 69
8	3. 00 ±7. 5%		6. 85
7	2. 30 ±7. 5%		6. 11
6	1. 70 ±7. 5%		5. 44
5	1. 30 ±7. 5%		4. 57
4	0. 96 ±7. 5%		4. 57
3	0. 73 ±7. 5%		4. 57
2	0. 56 ±7. 5%		4. 57
1	0. 40 ±7. 5%		4. 57

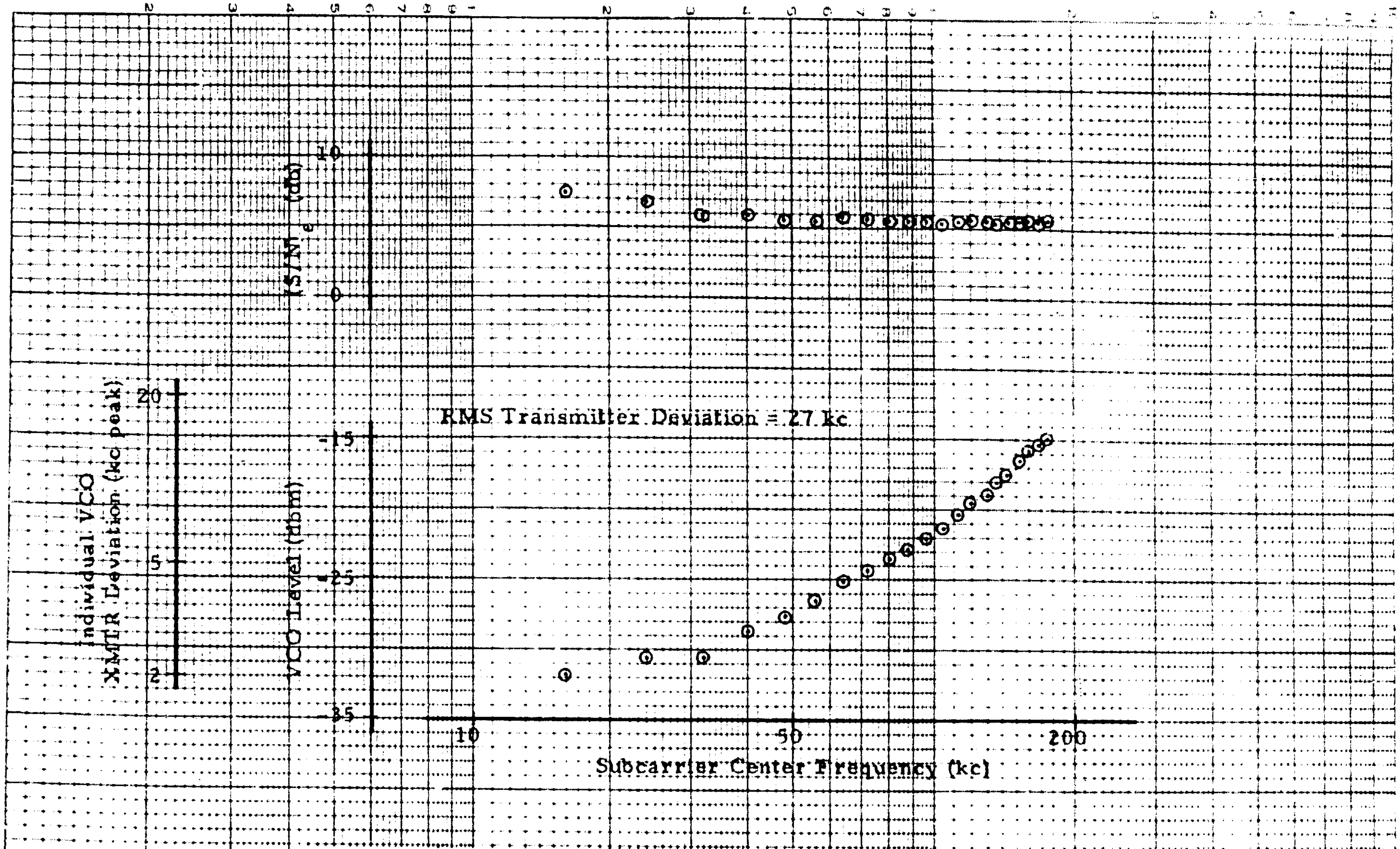


FIGURE I-3.2-8
PRE-EMPHASIS SCHEDULE FOR
CONSTANT BANDWIDTH MULTIPLEX

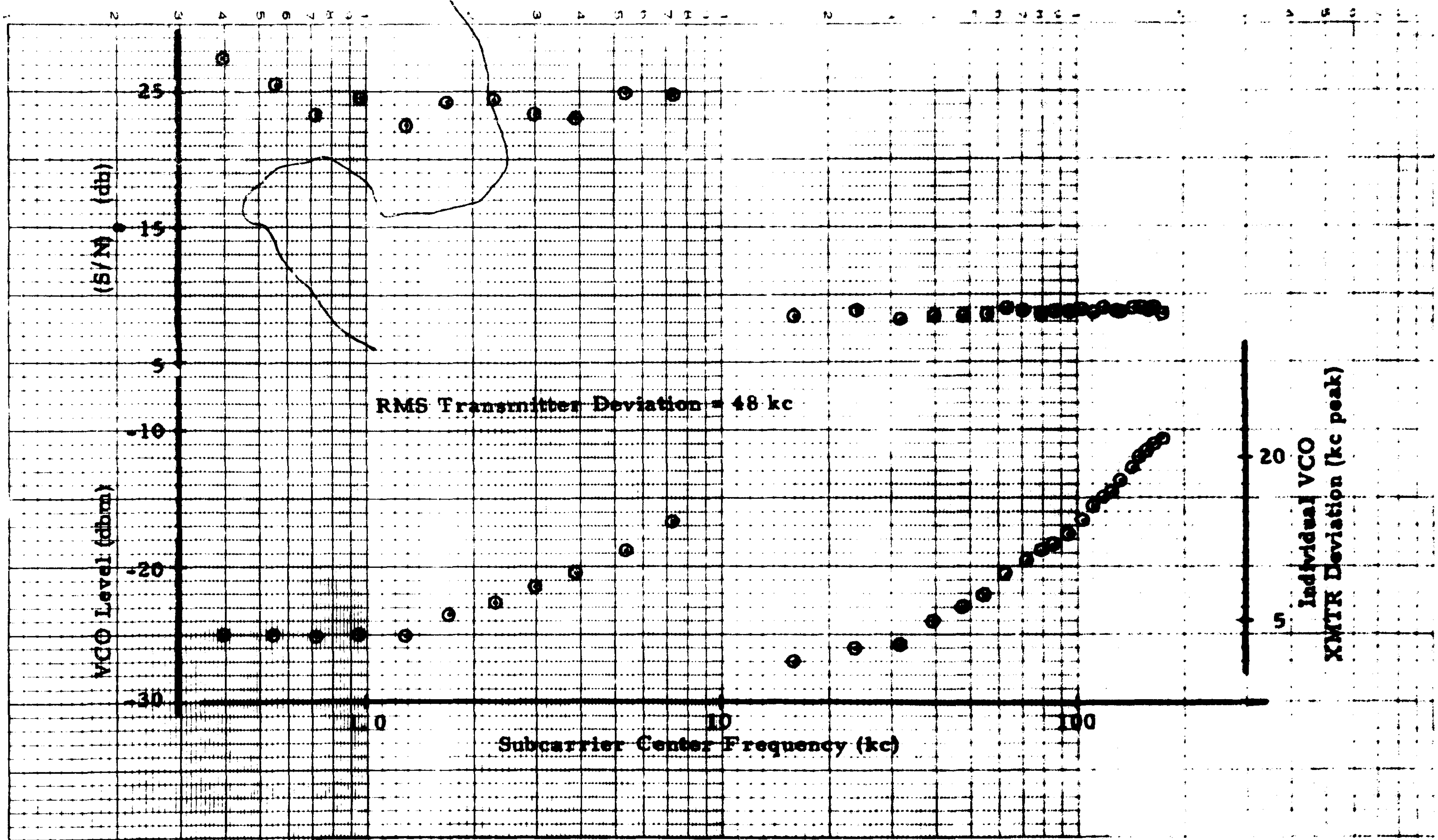


FIGURE I-3.2-9
PRE-EMPHASIS SCHEDULE FOR
COMBINATIONAL BANDWIDTH MULTIPLEX

3.3 RADIATED SPECTRUM

3.3.1 Proportional-Bandwidth Basebands

The constraint on the transmitter-radiated spectrum specified in the original contract for use in the experimental evaluation was as follows:

> The 40-db bandwidth of the modulated carrier, referenced to the unmodulated carrier, shall not exceed ±320 kc. Carrier components appearing outside a ±500-kc bandwidth shall not exceed −25 dbm.

During the course of the program, this specification was revised and used in a more specific form:

> The power spectral density, as measured in a 1000-cps bandwidth, outside a bandwidth of ±320 kc shall not exceed −50.5 db referenced to the unmodulated carrier. Carrier components outside a ±500-kc bandwidth shall not exceed −25 dbm.

The transmitter pre-emphasis for each baseband evaluated was optimized under the constraint of the revised radiated-spectrum specification.

Initially, an rf spectrum analyzer was used to measure the radiated spectrum; however, since the spectrum of the IRIG proportional-bandwidth multiplex proved to be continuous with no discrete lines, a quantitative measure using the analyzer was impossible. The major difficulties were: uncalibrated bandwidth, uncalibrated sweep rates, nonlinear amplitude display, and the necessity for averaging the continuous random spectra by eye. Figure I-3.3-1 is a photograph of the rf spectrum analyzer display showing the spectrum of the transmitter modulated with the IRIG narrowband multiplex.

A spectrum translation technique was devised (Figure I-3.3-2) to overcome the shortcomings of the spectrum analyzer and to make possible quantitative spectral measurements. By heterodyning the transmitter output with a local oscillator operating 1 Mc above or below the unmodulated transmitter frequency, the radiated spectrum can be measured with a frequency-selective voltmeter such as the Hewlett-Packard Model 310A Wave Analyzer. This instrument's narrow, calibrated bandwidth allows the average value of the energy to be measured accurately and the power spectral density of the transmitter to be plotted. The details of the measurement procedure are contained in Volume II, section 3.2

Figure I-3.3-3 shows the measured power spectral density of the IRIG 18-channel baseband with a total rms transmitter deviation of 75 kc. The shape of the spectrum was found to fit the gaussian (normal) probability density curve to within ±2 db out to four standard deviations (4σ). This shape has been theoretically predicted by Abramson,[1] who relates the rms modulating wave directly to the rms bandwidth (standard deviation) of the output spectra. The correlation is extremely close. As measured, the $\pm 3.5\sigma$ bandwidth was 560 kc, giving a standard deviation or rms bandwidth of 80 kc.

The results of the radiated spectrum test on the IRIG 18-channel baseband led to a revision of the radiated spectrum specification. A more meaningful specification which specified the rms bandwidth seemed warranted. Therefore, the radiated spectrum specification was changed to specify the $\pm 3.5\sigma$ bandwidth at ±320 kc; the "−25 dbm" specification (±500 kc) was not changed. This revised specification places 99.93% of the transmitter energy within the assigned bandwidth of ±320 kc. The angle marks on Figure I-3.3-3 show the limits of this specification. The level of the spectrum shown in this figure is below the specification limit to allow for a 0.01% (26 kc) center-frequency drift specification.

The radiated-spectrum-measurement technique requires the use of attenuators to reduce the power level to the dynamic range of the particular instruments used for the measurements. As long as measurements are made relative to the unmodulated carrier level the attenuators do not introduce errors; however, the −25 dbm portion of the specification is an absolute level dependent upon the actual transmitter output power. Thus, to provide a general solution, a 100-watt carrier level was assumed and the −25 dbm level was converted to an equivalent −75 db referred to the 100-watt unmodulated carrier level. The 100-watt level is the maximum allowed by IRIG Document No. 106-60 and represents a worst-case condition. When this portion of the radiated-spectrum limit was applied, the measurements were also made using the 1000-cps bandwidth. The angle marks on the radiated spectrum figures at ±500 kc represent the −75 db limit.

Figure I-3.3-4 shows the spectrum of the IRIG proportional-bandwidth multiplex with wideband (±15%) channel E included. This spectrum is virtually identical to the spectrum shown in Figure I-3.3-3 for the 18 narrowband channels.

With expansion of the baseband to include proportional-bandwidth channels at 93, 124, and 165 kc, the orderly gaussian spectrum was deteriorated by peaks rising in the continuous spectrum at the frequencies of the first and second sidebands of the new channels. The modulation index for the expanded baseband was insufficient for the gaussian approximation to be valid. These peaks on the measured radiated spectrum, as shown in Figure I-3.3-5, are not discrete lines but are actually continuous spectra. In the second group of peaks, the peak at ±289 kc from the carrier is the sum frequency of 165 kc and 124 kc. The relative levels among the peaks correspond closely to the relative levels that would occur with single-tone modulation at the same modulation index.

The revised radiated-spectrum specification, $\pm 3.5\sigma$ bandwidth at ±320 kc fits the

---

(1) N. Abramson, "Bandwidth and Spectra of Phase- and Frequency-Modulated Waves," <u>IEEE Trans. on Communications Systems, December</u> 1963.

guassian spectrum well; however, it is not precisely applicable to the nongaussian spectrum of the expanded baseband. Therefore, a re-interpretation of the specification was necessary. With the gaussian spectrum of the IRIG multiplex, the specified ±3.5σ bandwidth of ±320 kc occurred at −50.5 db, referenced to the unmodulated carrier level; therefore, this criterion of −50.5 db was applied to the nongaussian spectra. The resulting radiated-spectrum specification used throughout the remainder of the evaluation program was:

> The power spectral density, as measured in a 1000-cps bandwidth, outside a bandwidth of ±320 kc shall not exceed −50.5 db referenced to the unmodulated carrier. Carrier components outside a ±500-kc bandwidth shall not exceed −25 dbm.

The application of this specification to the expanded 21-channel baseband necessitated a reduction of the rms transmitter deviation to 56 kc.

Figure I-3.3-6 shows the radiated spectrum for the expanded proportional-bandwidth multiplex with wideband (±15%) channel H included. The spectrum due to this multiplex contained even greater peaks due to the high-frequency channels. This necessitated reducing the rms transmitter deviation to 47 kc.

3.3.2 Constant- and Combinational-Bandwidth Basebands

An identical procedure for measuring the radiated spectrum was used in the evaluation of the constant- and combinational-bandwidth basebands. For the constant-bandwidth multiplex, with VCOs at center frequency and unmodulated, the radiated spectrum consisted of discrete lines spaced 8 kc apart as shown in Figure I-3.3-7. (In the following figures the carrier is shown at the origin and only one side of the spectrum is plotted for clarity. Measurements were made to ascertain that the spectrum is symmetrical about the carrier.) The first line, 8 kc from the carrier, is the difference frequency between each adjacent channel and the 8-kc component of other higher-order product frequencies. The next group of lines from 16 kc, at the subcarrier frequencies, are the constant-bandwidth first-order sidebands and various product, sum, and difference frequencies which are again 8 kc apart. The lines in this group are of equal level because the pre-emphasis schedule provided nearly equal transmitter modulation indices for the individual VCOs. The lines beyond the last constant-bandwidth subcarrier center frequency are due to second-order sidebands and the sum frequencies of the various sideband products. These also occur at equal 8-kc spacing.

The application of the evolved radiated-spectrum specification to the observed discrete-line spectrum to determine the allowable transmitter drive again appeared inappropriate. The original specification was adequate for line spectra but not applicable to the continuous spectra obtained with the proportional-bandwidth basebands. It appeared that perhaps the original specification ("The 40 db bandwidth of the modulated carrier, referenced to the unmodulated carrier shall not exceed ±320 kc. Carrier components appearing outside a ±500 kc bandwidth shall not exceed −25 dbm.") should be used; however, upon further investigation, it was found that the controlling specification was −25 dbm (−75 db for a

100-watt carrier) at ±500 kc. Thus, either specification provides the same maximum allowable transmitter deviation of 27 kc rms.

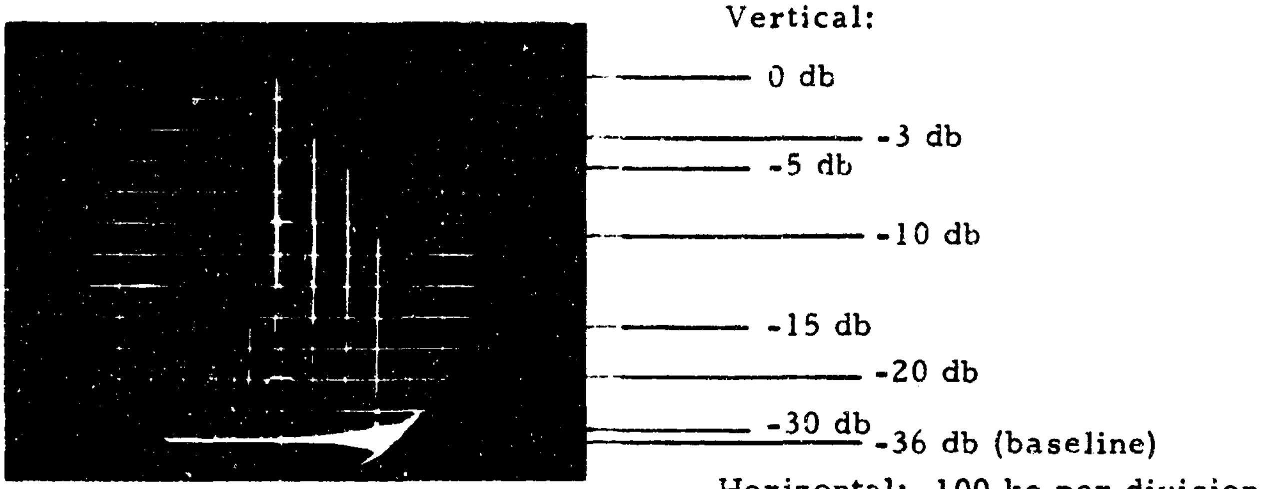
One might speculate that making the spacing from dc to the first channel an amount that is not a multiple of the channel spacing would prevent the superposition of the sidebands and product terms, thus reducing the radiated spectrum level. A test was made with all channels at low bandedge (i.e., the first channel at 14 kc). The change in radiated spectrum level was found to be less than 1 db when measured with an instrument with a sharply defined 1.0-kc bandwidth. There is such an infinity of terms and possible combinations that the spectrum is virtually unchanged.

Figure I-3.3-8 shows the radiated spectrum for the constant-bandwidth multiplex with only channels 1 through 16 present. This baseband was not evaluated in the remainder of the system test (as discussed in section 3.2). Rather the 21-channel multiplex was evaluated.

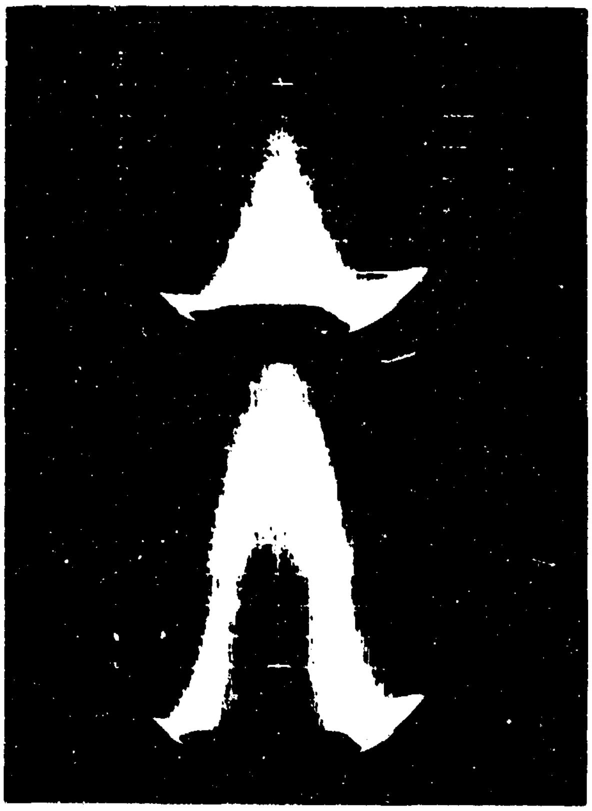
Figure I-3.3-9 shows the measured radiated spectrum for the combinational-bandwidth multiplex. The addition of the 11 IRIG channels to the constant-bandwidth baseband caused the line spectrum to spread into a continuous spectrum of reduced magnitude. The reduction in the radiated-spectrum level allowed the rms transmitter deviation to be increased from 27 kc to 48 kc. The resulting increase in transmitter deviation due to each VCO provided an increased subcarrier level at the receiver output and, thereby, an increase in subcarrier-to-noise ratio with no increase in rf bandwidth. Figures I-3.3-10 and I-3.3-11 are photographs of an rf psectrum analyzer display showing the effect of the IRIG channels on the constant-bandwidth multiplex radiated spectrum.

The detailed procedure used for measuring the radiated spectrum as well as the measured data are contained in Volume II, section 3.2.

a. Scale Calibration
Vertical:



Horizontal: 100 kc per division



b. IRIG RF Spectrum

RMS Transmitter Deviation: 75 kc

Preemphasis: Linear Taper

c. Same as b above with 20 db attenuation removed.

FIGURE I-3. 3-1
RF SPECTRUM DISPLAY OF IRIG PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 THROUGH 18

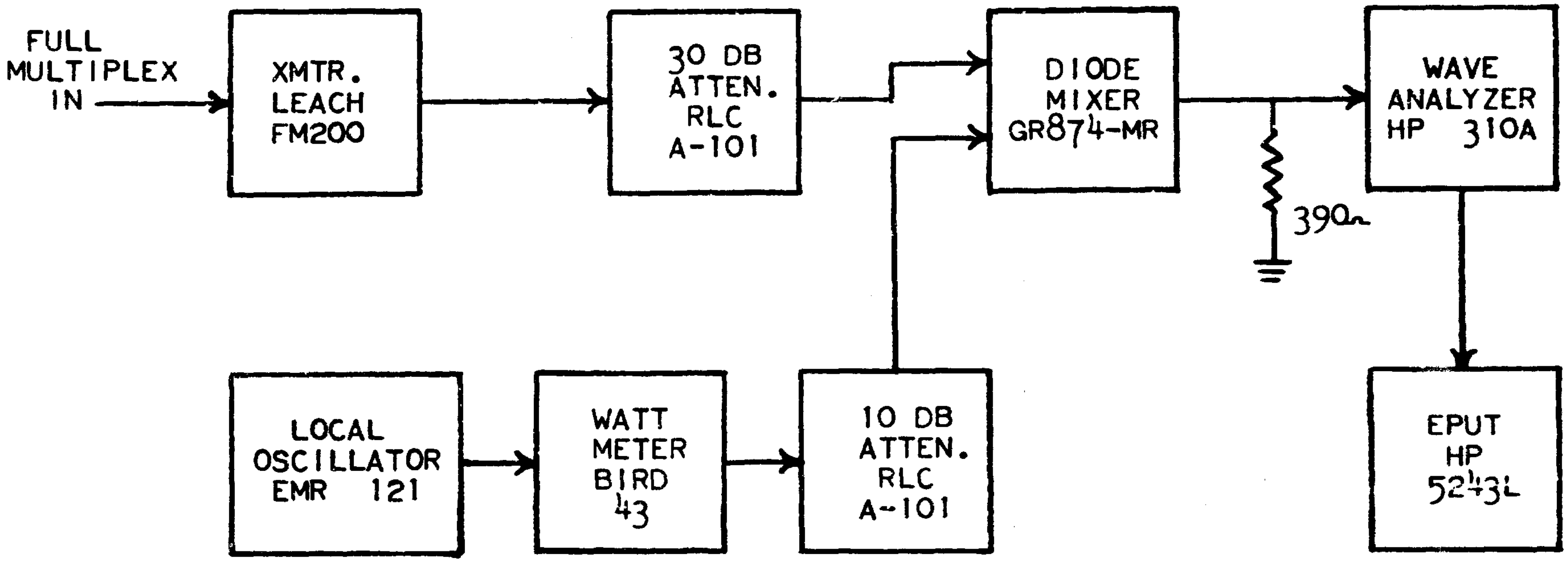


FIGURE I-3.3-2
TRANSMITTER RADIATED SPECTRUM
TEST BLOCK DIAGRAM

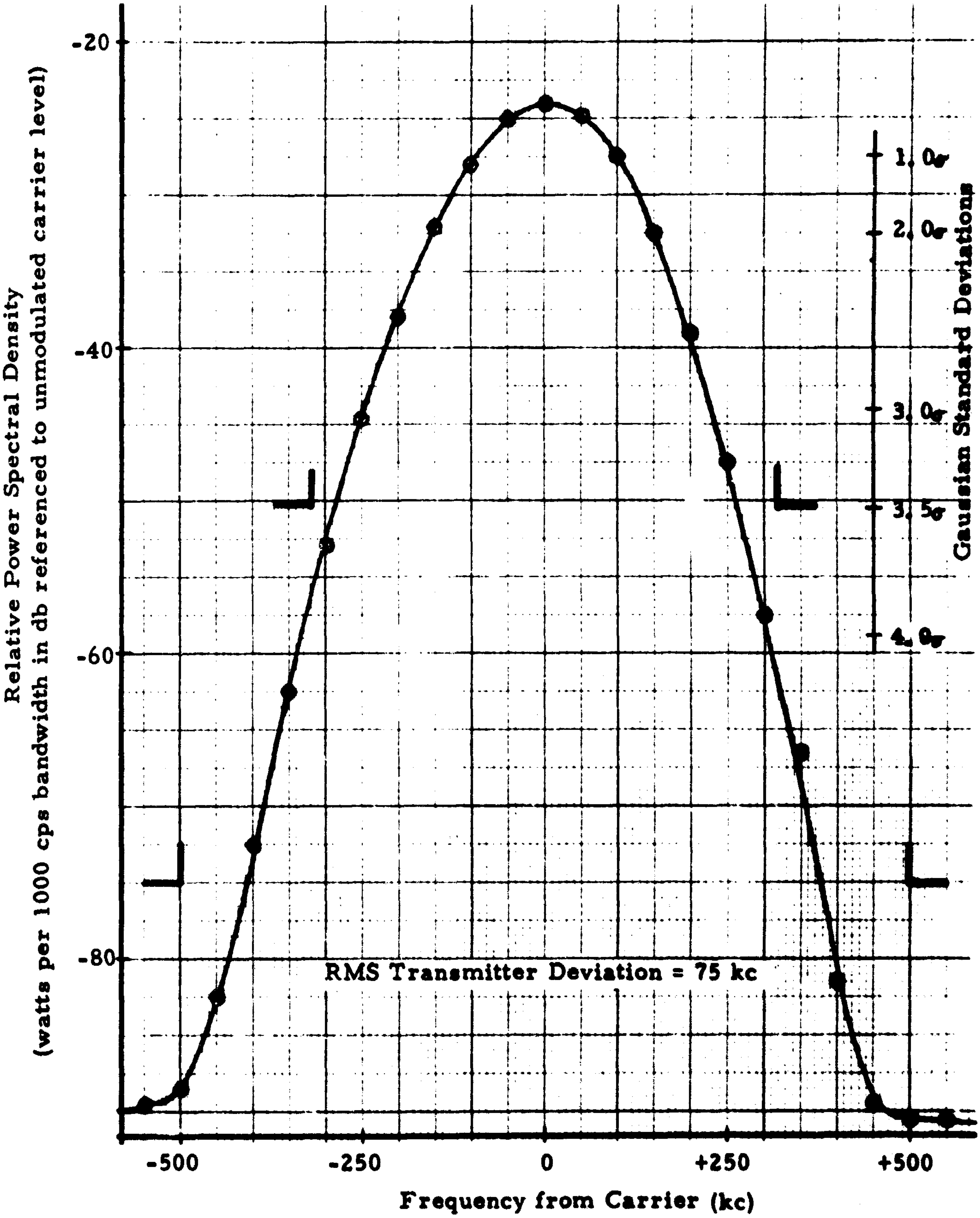


FIGURE I-3. 3-3
TRANSMITTER RADIATED SPECTRUM FOR IRIG PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 THROUGH 18

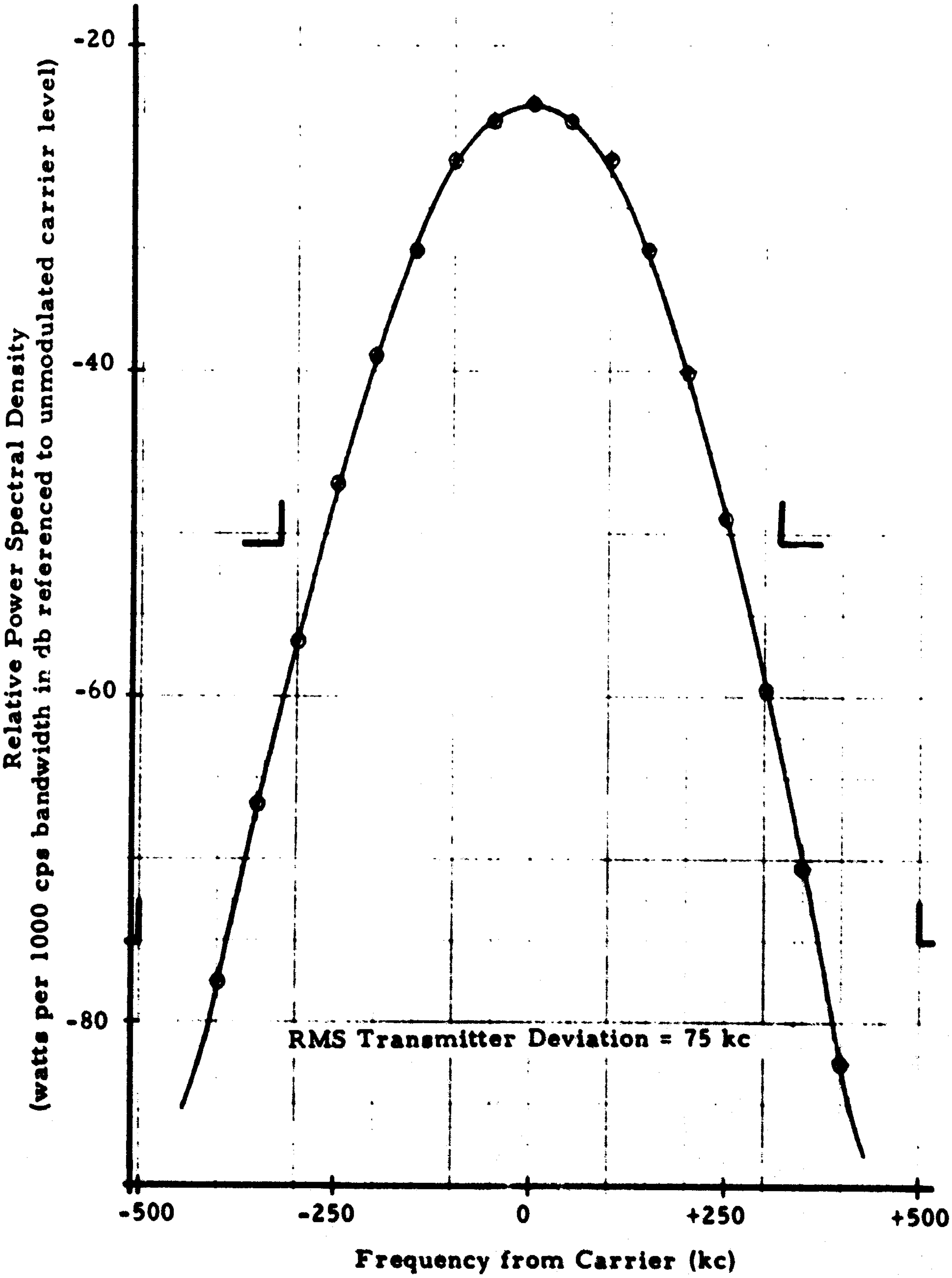


FIGURE I-3. 3-4
TRANSMITTER RADIATED SPECTRUM FOR IRIG
PROPORTIONAL BANDWIDTH MULTIPLEX,
CHANNELS 1 THROUGH 16 AND E

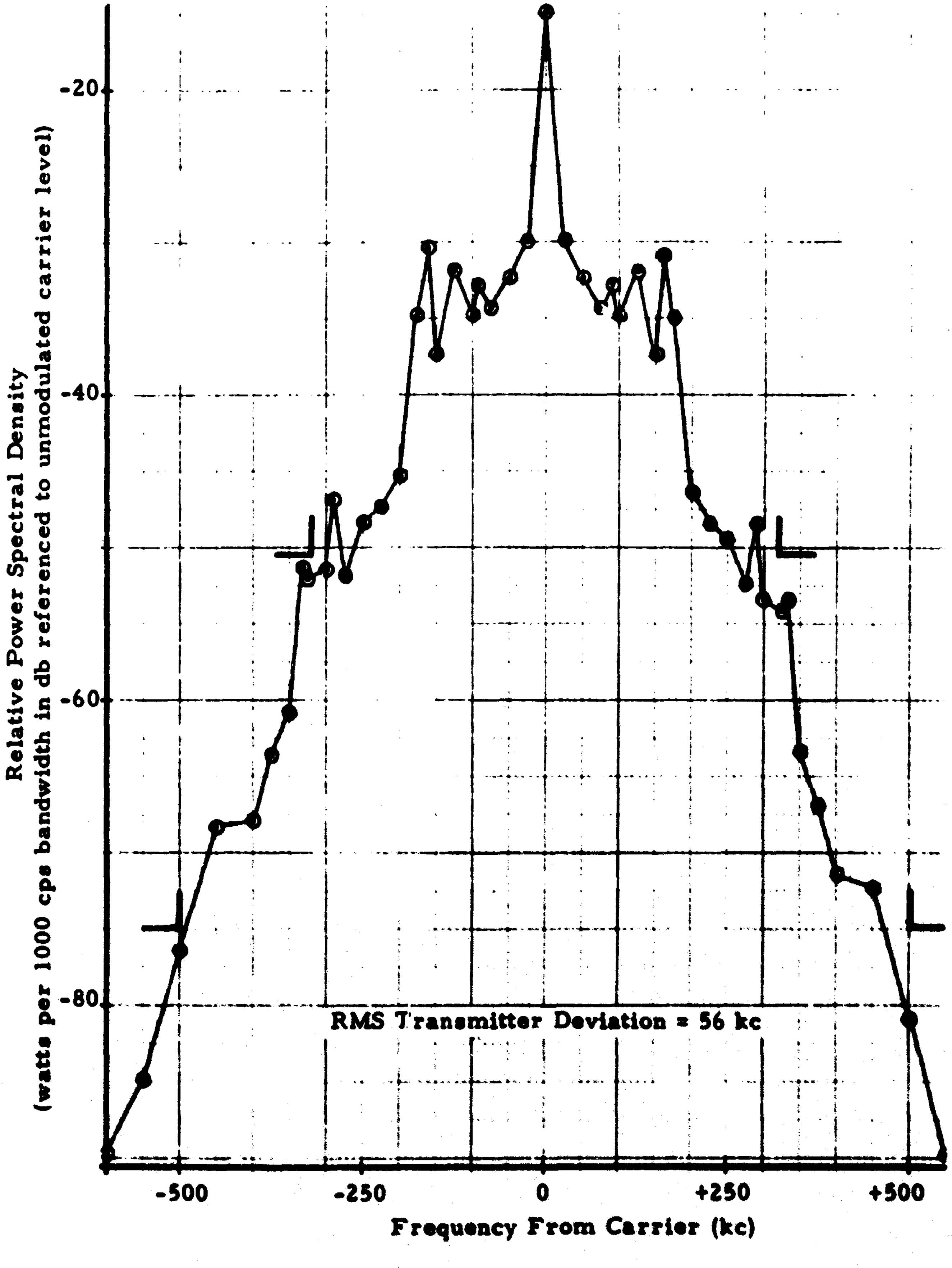


FIGURE I-3. 3-5
TRANSMITTER RADIATED SPECTRUM FOR EXPANDED PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 THROUGH 21

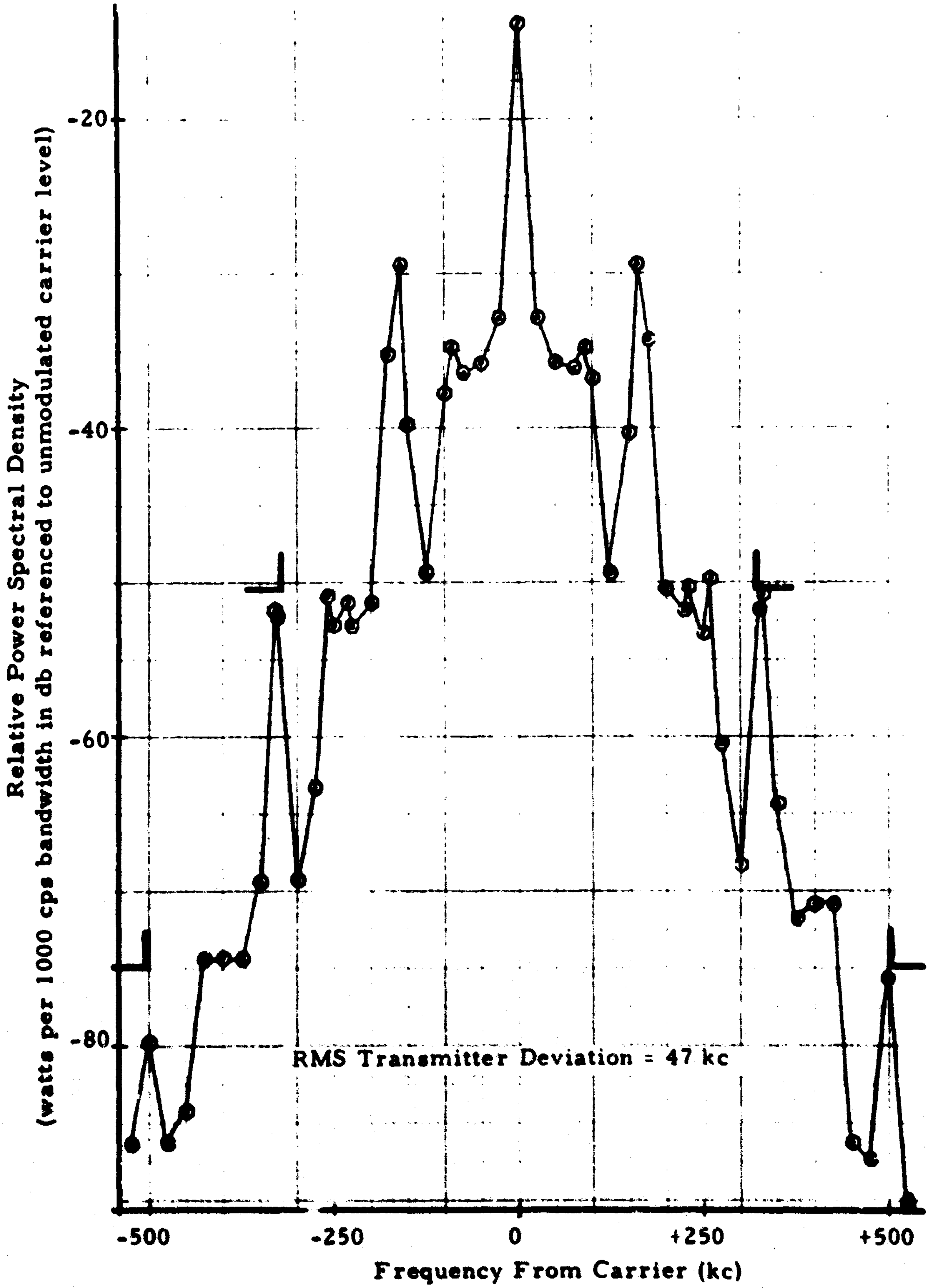


FIGURE I-3. 3-6
TRANSMITTER RADIATED SPECTRUM FOR EXPANDED
PROPORTIONAL BANDWIDTH MULTIPLEX,
CHANNELS 1 THROUGH 19 AND H

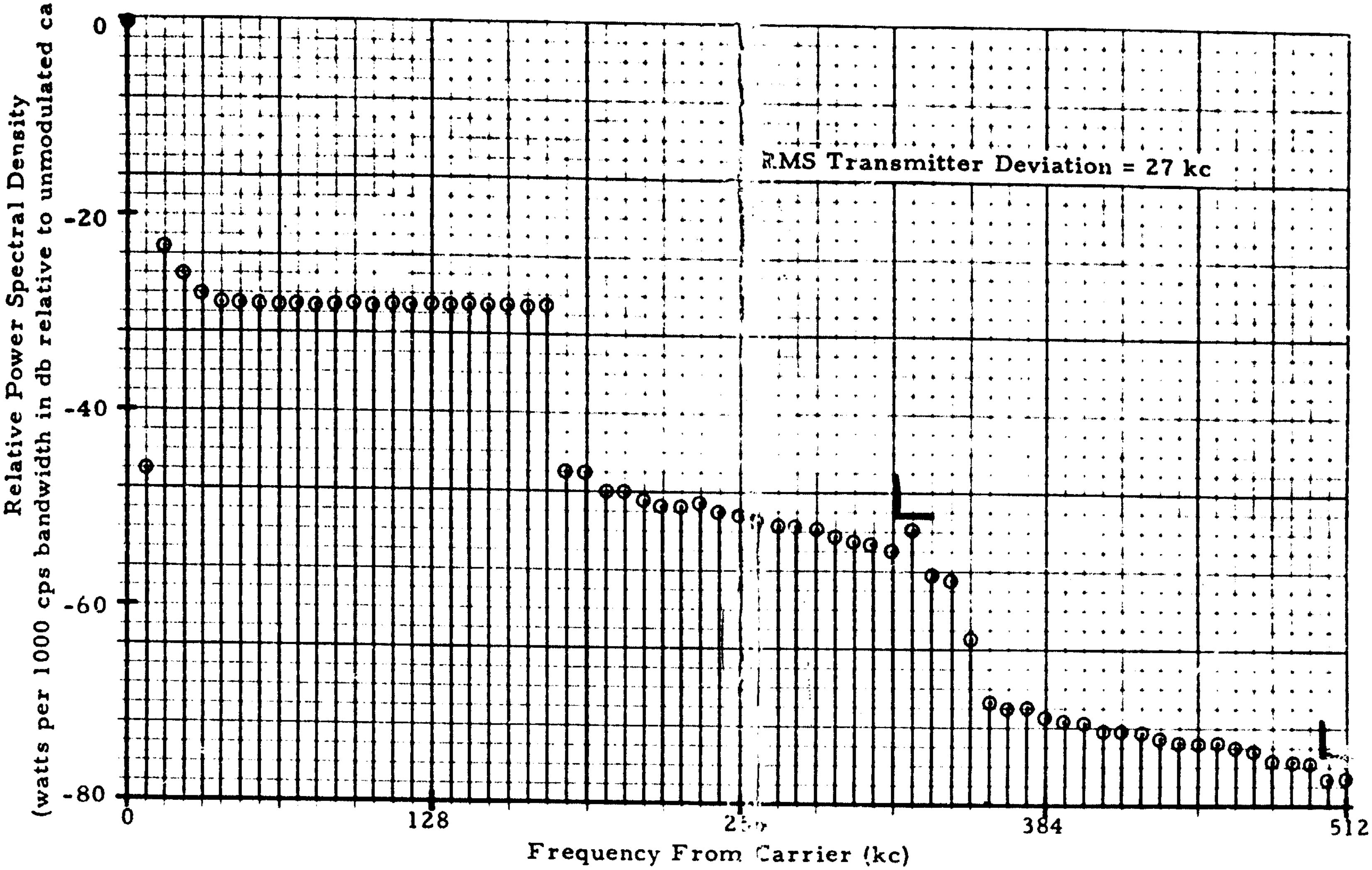


FIGURE I-3.3-7

TRANSMITTER RADIATED SPECTRUM FOR CONSTANT BANDWIDTH MULTIPLEX CHANNELS 1 THROUGH 21

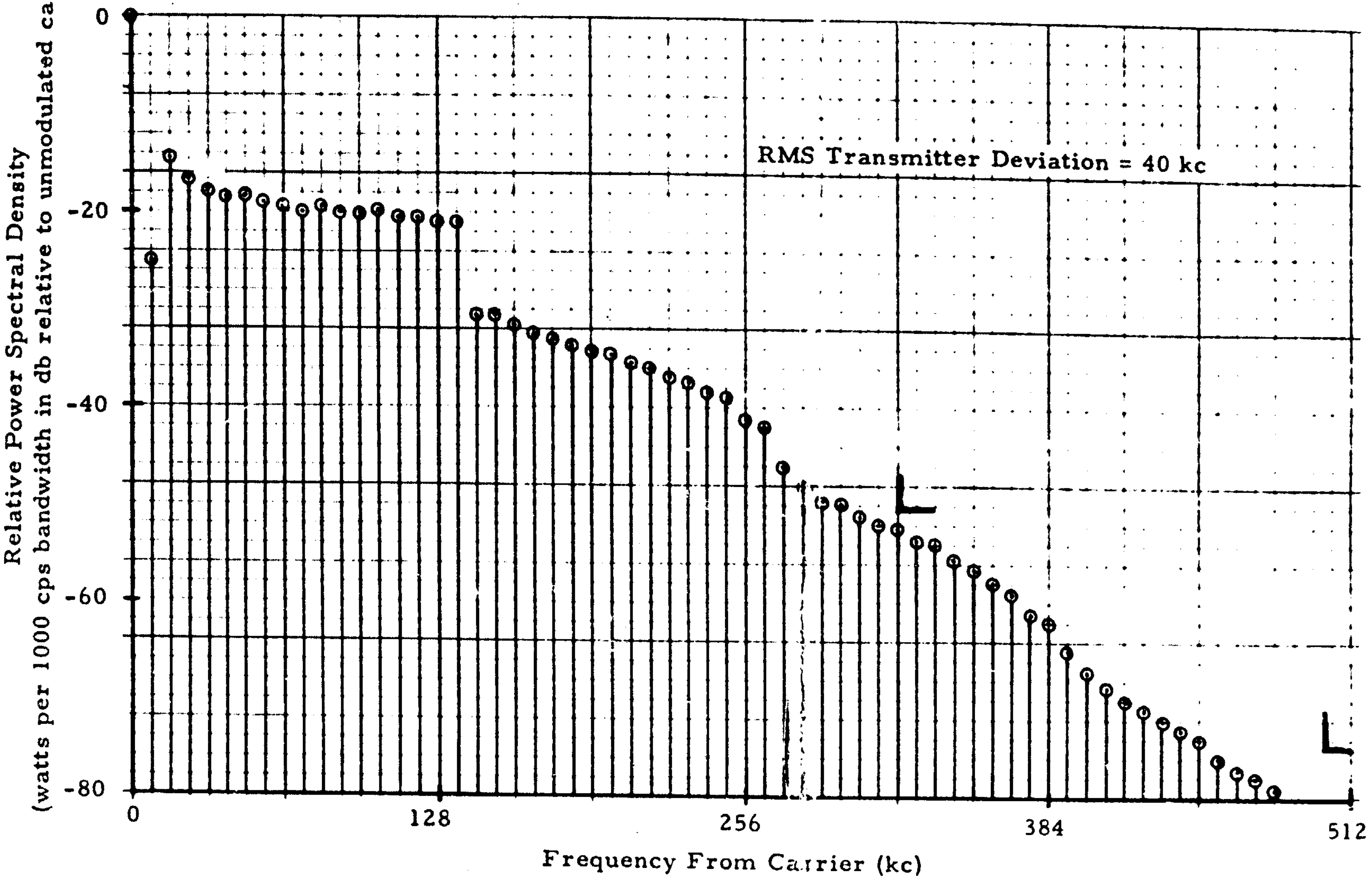


FIGURE I-3.3-8
TRANSMITTER RADIATED SPECTRUM FOR CONSTANT BANDWIDTH MULTIPLEX
CHANNELS 1 THROUGH 16

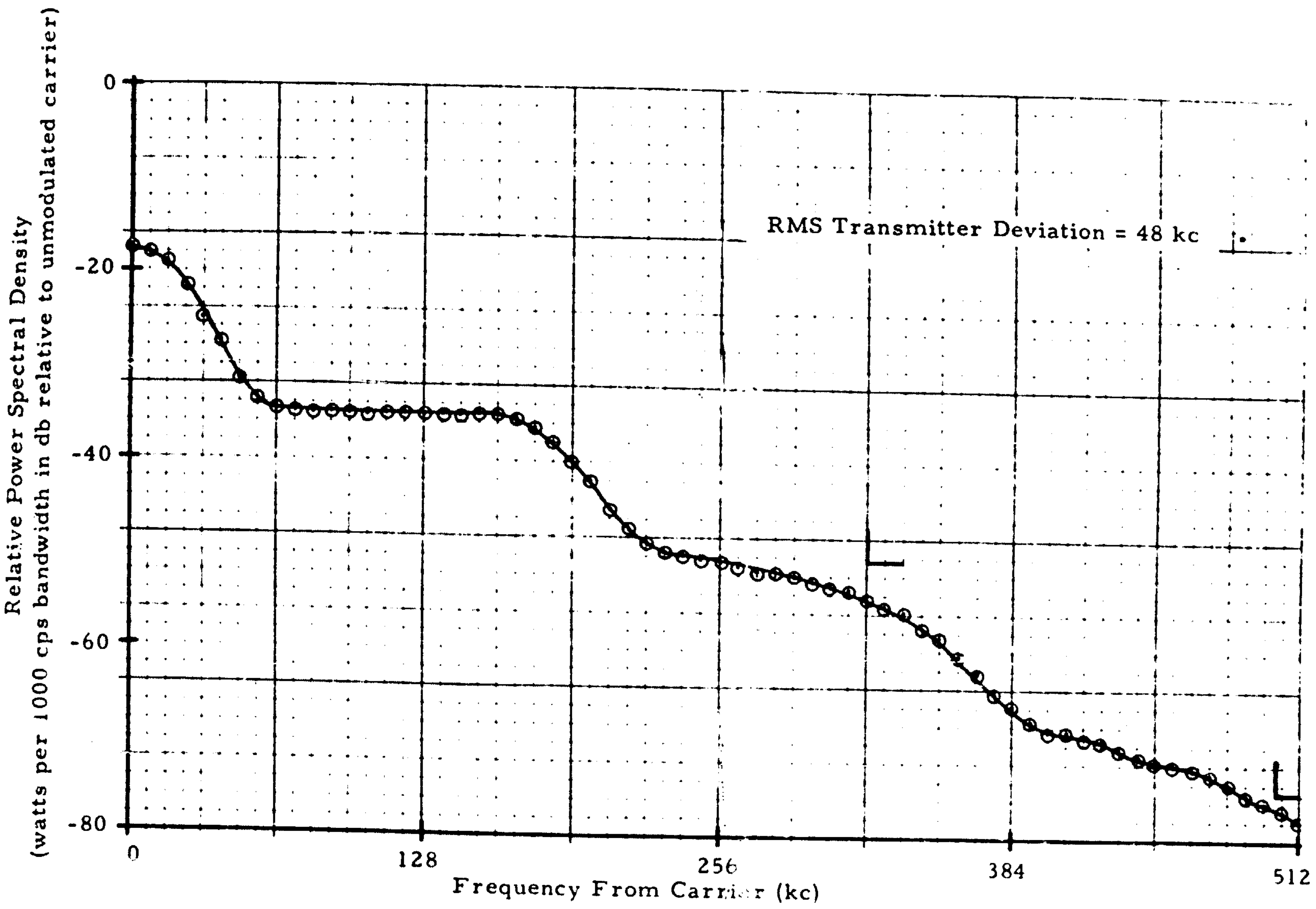
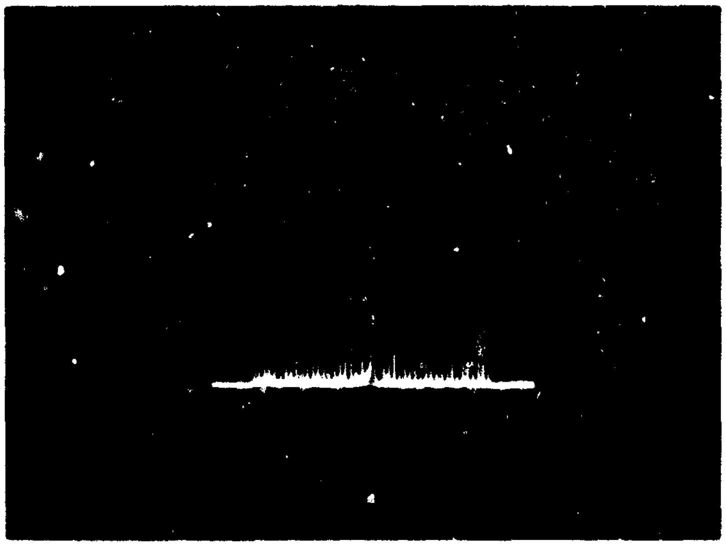


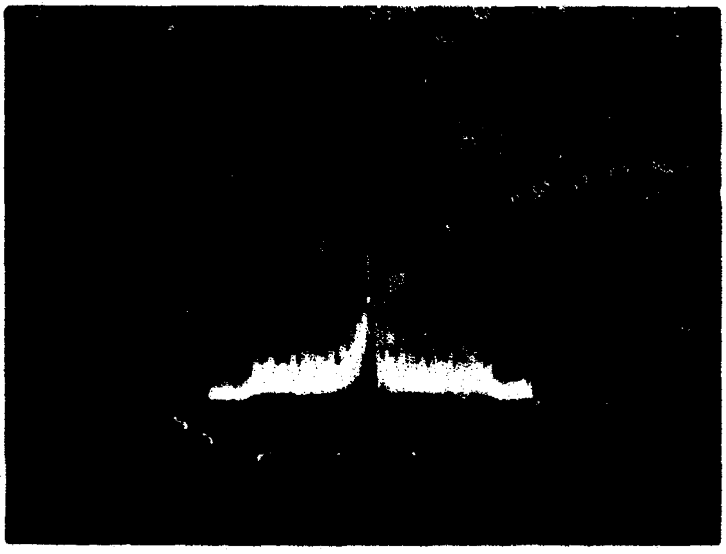
FIGURE I-3. 3-9
TRANSMITTER RADIATED SPECTRUM FOR COMBINATIONAL BANDWIDTH MULTIPLEX



Vertical Calibration

0
3 db
6 db
9 db
12 db
15 db
18 db
22 db
28 db
baseline

CONSTANT BANDWIDTH RF SPECTRUM
(Horizontal Calibration: 50 kc per division)

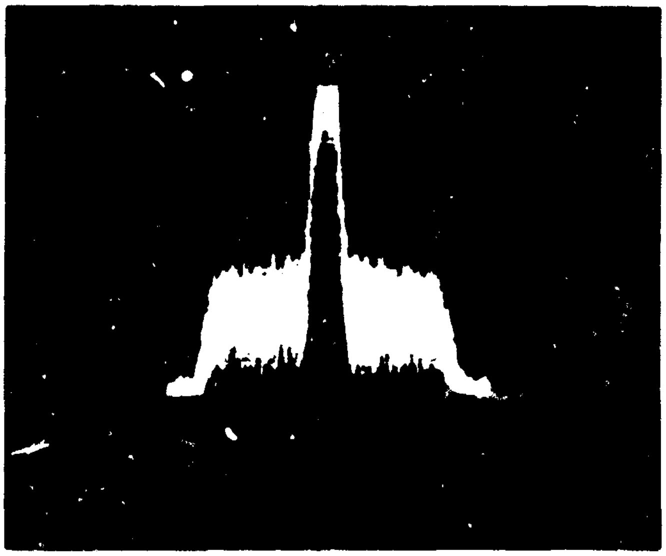


Total RMS Transmitter Deviation· 27 kc

CONSTANT BANDWIDTH RF SPECTRUM
(20 db attenuation removed)

FIGURE 1-3, 3-10

RF SPECTRUM DISPLAY OF 21-CHANNEL CONSTANT-BANDWIDTH MULTIPLEX

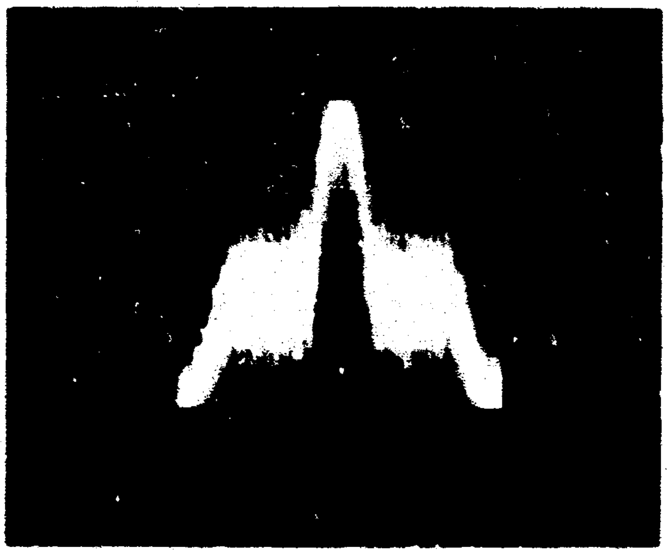


Total RMS
Transmitter
Deviation:
28.6 kc

Constant Bandwidth:
27 kc rms

IRIG Channels:
9.4 kc rms

ELEVEN IRIG CHANNELS ADDED
TO CONSTANT BANDWIDTH
MULTIPLEX



Total RMS
Transmitter
Deviation:
47.5 kc

Constant Bandwidth:
45 kc rms

IRIG Channels:
15.8 kc rms

COMBINATIONAL BANDWIDTH
MULTIPLEX RF SPECTRUM ADJUSTED
TO SAME BANDWIDTH AS FIGURE I-3.3-10b.

FIGURE I-3.3-11

RF SPECTRUM DISPLAY OF 32-CHANNEL
COMBINATIONAL BANDWIDTH MULTIPLEX

3.4 INTERMODULATION

System output noise due to intermodulation products (including crosstalk) was measured on each system with all channels except the channel under investigation (search channel) deviating full bandwidth at a rate of either one-tenth nominal channel cutoff frequency or 5 cps, whichever was larger. The search channel VCO was deviated slowly from bandedge to bandedge while the peak-to-peak intermodulation noise level at the subcarrier discriminator output was measured by photographing an oscilloscope display. To ensure synchronization of the discriminator output and calibration accuracy, the horizontal sweep voltage of the oscilloscope was used to deviate the search channel VCO. The sweep speed used was 5 sec/cm, or 40 seconds for full-bandwidth deviation. In addition to the photographic display, the maximum rms output voltage was also determined. The block diagram of the test is shown in Figure I-3.4-1; other details are contained in Volume II, section 3.4.

3.4.1 Proportional-Bandwidth Basebands

Table I-3.4-2 summarizes the intermodulation data for the IRIG proportional-bandwidth baseband operating at deviation ratios of 5, 2, and 1. The first column shows the peak-to-peak intermodulation noise as determined from the photographs of the search channel output. This data has been converted to percent of full-scale peak-to-peak output voltage. The second column shows the maximum rms voltage measured as the search channel was swept from bandedge to bandedge. This data has also been scaled to percent of full-scale peak-to-peak output voltage.

Table I-3.4-3 is a summary of the intermodulation data for the IRIG baseband including wideband (±15%) channel E and the expanded proportional-bandwidth basebands. There was no significant difference in the subcarrier discriminator output noise due to intermodulation products between system operation with the 18-channel IRIG system and the 21-channel expanded system. With each baseband changed to include a wideband (±15%) channel in the highest frequency position, no increase in output noise due to intermodulation was obtained. Changing th operation of the IRIG system from a deviation ratio of 5 to deviation ratios of 2 and 1, however, caused a marked increase in intermodulation noise.

3.4.2 Constant- and Combinational-Bandwidth Basebands

Table I-3.4-4 is a summary of the intermodulation data for the constant-bandwidth baseband operated at a deviation ratio of 2. Data was obtained on each channel with all other channels deviated full bandwidth at one-tenth the nominal cutoff frequency (i.e., a modulation index of 20). Also, representative channels in each group were investigated with all other channels deviated full bandwidth at maximum cutoff frequency (modulation index equal to 2) and with all other channels at center frequency unmodulated. No significant differences in intermodulation products were observed between modulation indices of 2 and 20; however, there was a definite increase in intermodulation noise with all other channels at center frequency. This condition is to be expected with an equally-spaced constant-bandwidth baseband and was apparent from the "bow tie" shape of the intermodulation noise seen about the center-frequency position of the search channel when all the other channels are modulated (see Figure II-3.3-2 in Volume II). Although the intermodulation is maximum with all channels at center frequency, this modulation condition is a special case which seldom occurs when data is being transmitted.

Data was obtained on intermodulation for the constant-bandwidth baseband operated at deviation ratios of 1 and 4 and is summarized in Table I-3.4-5. For ease of comparison, the same representative channels from each group were chosen for investigation. The modulation conditions for all other channels in the multiplex were again: modulation index of 2, modulation index of 20, and all channels at center frequency unmodulated. The data for a deviation ratio of 2 has been repeated from Table I-3.4-4 for reference.

The effect of intermodulation on the combinational-bandwidth baseband was determined with the search channel operated at a deviation ratio of 2 for the constant-bandwidth channels and at a deviation ratio of 5 for the IRIG channels. All other channels in the multiplex were deviated full bandwidth at one-tenth their respective nominal cutoff frequencies. Table I-3.4-6 is a summary of this data. Additional data was obtained on IRIG channel 11 and constant-bandwidth channel 1 when IRIG channel 12 was added to the multiplex. Channel 12 was not used because the channel spacing between channel 12 and channel 1 was thought to be insufficient. The data indicates that there was no degradation in performance of the adjacent channels with the addition of channel 12.

For better familiarity with the operation of the constant-bandwidth baseband, several modifications were made to the laboratory system and the intermodulation data was repeated. Tables I-3.4-7 and I-3.4-8 summarize this data. Table I-3.4-7a. shows the effect of reducing the number of poles in the subcarrier discriminator output filter from seven (42 db per octave) to three (18 db per octave). No significant differences are observable because the intermodulation products fall at the center of the data passband. For constant-bandwidth basebands that are constructed so that the intermodulation beats fall at or just beyond bandedge, the advantage of greater attenuation in the output filter would be obvious.

Table I-3.4-7b. shows the effect that the rf link has on intermodulation products. This data was obtained by bypassing the transmitter and receiver and clearly illustrates that the rf link is the major contributor to intermodulation noise at the system output. To further isolate the cause of the intermodulation, the DEI TMR-2A Receiver was substituted for the Nems-Clarke Model 1455A that had been used throughout the system evaluation. This data is summarized in Table I-3.4-7c. and shows no significant change in intermodulation level.

Table I-3.4-8 shows a summary of intermodulation data obtained by substituting the EMR Model 246A for the Leach FM 200 Transmitter (which had been used throughout the system evaluation) and by making other system modifications. All the data in this table was obtained by investigating only channel 6 with the normal 42-db-per-octave output filter. Table I-3.4-8a. shows that no significant improvement was obtained by changing only the transmitter. Table I-3.4-8b. indicates that the substitution of a special-purpose receiver with a 1.0 Mc IF bandwidth reduced the intermodulation level from 4.5% to 4.0%. This is misleading since the rf level was identical to that used with the other receivers; however, the noise level at the channel-6 output increased significantly. Also, the characteristic "bow tie" intermodulation effect is not present. (See Figure II-3.3-60 in Volume II.) The correct conclusion is that the intermodulation level does indeed decrease with the use of a wider IF bandwidth (i.e., an increase from 500 kc to 1.0 Mc).

Table I-3.4-8c. shows the effect of using separate modulation sources to deviate all other channels during the intermodulation test with the EMR 246A Transmitter and the Nems Clarke 1455A Receiver. With reference to the block diagram for the constant-bandwidth system test (Figure I-3.1-2), even HP 200CD Oscillators were used to deviate the 21 constant-bandwidth VCOs. The channels that were deviated by the same oscillator were separated by seven channels spaced 8 kc apart. Thus, the channels that caused a beat at 56 kc were all correlated. As an example, HP 200CD Oscillator No. 7 deviated channel 7 (64 kc ±2 kc), channel 14 (120 kc ±2 kc), and channel 21 (176 kc ±2 kc). The difference frequency between each of these channels was 56 kc, which fell into channel 6 (56 kc ±2 kc), The other modulation sources also produced an identical effect. The effect of using 21 separate uncorrelated modulation sources is to remove the "bow tie" characteristic (see Figure II-3.3-60 in Volume II). The total intermodulation noise level does not decrease.

The next test performed with the EMR 246A Transmitter was to isolate intermodulation noise from normal receiver noise by operating the system at a a 39-db carrier-to-noise ratio. Figure I-3.7-8d. summarizes this data with the conclusion that a large percent of the total peak-to-peak channel noise is contributed by normal receiver noise. It is difficult to estimate the exact peak-to-peak contribution due to intermodulation, since the addition of the two noise sources may vary between direct peak and quadrature addition. Thus, combining the results of Table I-3.4-8a, and d., the true intermodulation noise on channel 6 may vary between 2.0% and 3.7% of full bandwidth.

In an effort to further define the intermodulation effect as being caused by the receiver IF, two other tests were performed. First the number of channels in the multiplex was reduced to 16 (group D was removed), and the transmitter deviation was readjusted to the same total rms deviation. The results of this test, shown in Table I-3.4-8c., were that the intermodulation was reduced to the noise level of the channel. The second test consisted of reducing the level of the multiplex (including group D) to one-half its normal level. The results of this, shown in Table I-3.4-8d., were that the intermodulation level is unaffected.

The conclusions from the various intermodulation tests are that the worst-case intermodulation measured for the constant-bandwidth multiplex is on channel 6, and the peak-to-peak level including noise is 6.2% of full bandwidth. The average intermodulation on the other channels was 3.4% of full bandwidth. Operation of the constant-bandwidth system at a deviation ratio of 1 increases the intermodulation noise by a factor of 2 to a level which may make operation at this deviation ratio undesirable. The intermodulation is improved by almost a factor of 5 by increasing the deviation ratio to 4. For the combinational-bandwidth baseband, the maximum peak-to-peak intermodulation level measured, including receiver noise, was 6.5% of full bandwidth, and the average for the other constant-bandwidth channels was 5.0% of full bandwidth. The peak-to-peak level of the intermodulation on the IRIG channels of the combinational-bandwidth multiplex was less than 0.5% of full bandwidth. From the various additional tests, it was concluded that the intermodulation is primarily caused by the receiver IF. Although no formal tests were made, the system evaluated may be an optimum compromise between intermodulation generated in the IF and normal receiver noise; i.e., a wider IF will reduce the intermodulation level but will cause the receiver to threshold at a higher carrier-to-noise ratio.

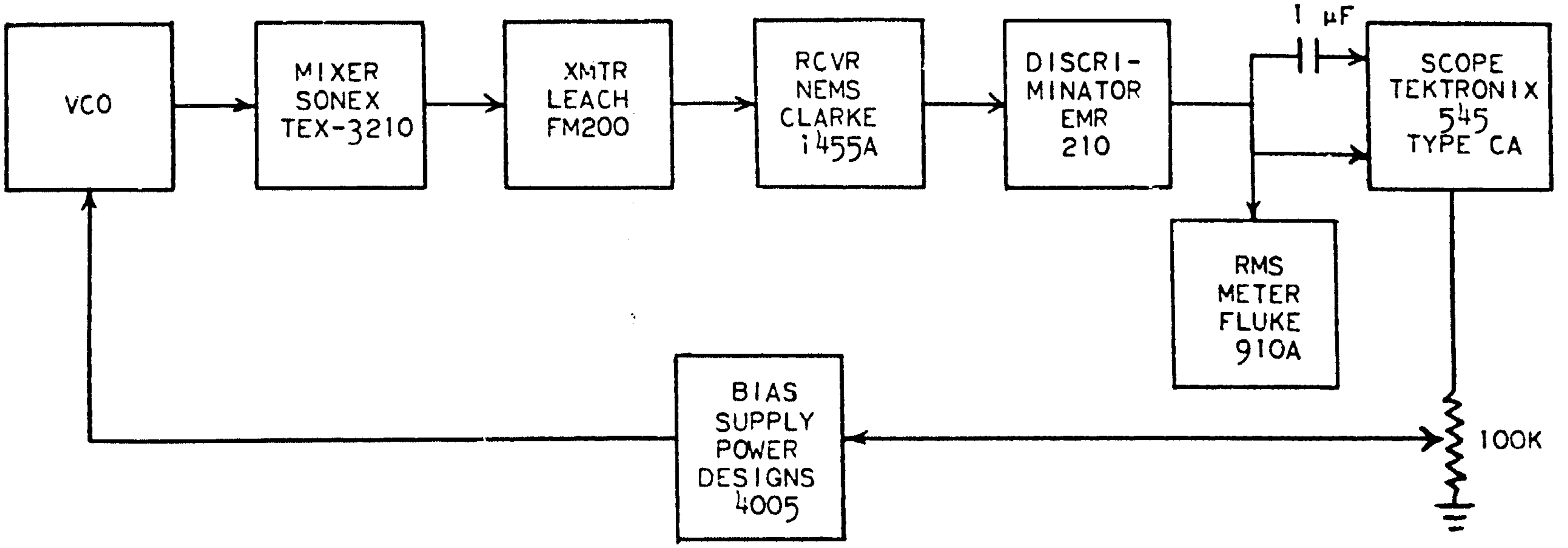


FIGURE I-3.4-1
INTERMODULATION TEST BLOCK DIAGRAM

TABLE I-3.4-2
SUMMARY OF INTERMODULATION DATA: IRIG MULTIPLEX FOR DEVIATION RATIOS OF 1, 2, AND 5

Channel		DR = 5		DR = 2		DR = 1	
No.	Frequency (kc)	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW
1	0.40	0.7	0.07	1.4	0.23	2.5	0.45
2	0.56	0.4	0.06	2.0	0.25	10.5	1.50
3	0.73	0.6	0.10	6.5	1.40	30.0	5.25
4	0.96	0.5	0.08	3.5	0.65	19.0	3.15
5	1.3	0.6	0.09	1.8	0.25	4.5	0.55
6	1.7	0.4	0.08	1.8	0.22	6.5	1.20
7	2.3	0.6	0.08	1.8	0.22	6.5	0.70
8	3.0	0.5	0.08	5.0	0.85	20.0	3.40
9	3.9	0.7	0.08	2.5	0.38	9.0	1.50
10	5.4	0.8	0.09	2.3	0.26	3.5	0.42
11	7.35	0.7	0.08	2.5	0.35	7.5	0.85
12	10.5	0.8	0.10	2.5	0.22	3.0	0.45
13	14.5	0.9	0.10	2.8	0.22	4.5	0.50
14	22.0	0.8	0.10	3.2	0.39	6.5	1.00
15	30.0	0.9	0.10	3.8	0.40	9.0	1.25
16	40.0	0.9	0.10	4.0	0.45	10.0	1.75
17	52.5	1.0	0.12	3.8	0.40	10.0	1.50
18	70.0	0.8	0.10	4.0	0.45	10.5	1.75

TABLE I-3.4-3
SUMMARY OF INTERMODULATION DATA: PROPORTIONAL BANDWIDTH MULTIPLEX FOR DEVIATION RATIO OF 5

Channel		Channels 1-16 and E		Channels 1-21		Channels 1-19 and H	
No.	Frequency (kc)	Peak-Peak % FBW	Max rms % FBW	Peak-Peak % FBW	Max rms % FBW	Peak-Peak % FBW	Max rms % FBW
1	0. 40±7. 5%	0. 6	0. 14	0. 3	0. 1	0. 6	0. 12
2	0. 56±7. 5%	0. 5	0. 115	0. 6	0. 125	0. 5	0. 10
3	0. 73±7. 5%	0. 6	0. 13	0. 4	0. 09	0. 6	0. 11
4	0. 96±7. 5%	0. 5	0. 075	0. 4	0. 065	0. 4	0. 08
5	1. 3 ±7. 5%	0. 5	0. 09	0. 6	0. 1	0. 5	0. 08
6	1. 7 ±7. 5%	0. 5	0. 075	0. 6	0. 09	0. 5	0. 075
7	2. 3 ±7. 5%	0. 5	0. 07	0. 4	0. 075	0. 5	0. 085
8	3. 0 ±7. 5%	0. 4	0. 06	0. 4	0. 075	0. 6	0. 075
9	3. 9 ±7. 5%	0. 4	0. 0625	0. 4	0. 075	0. 6	0. 08
10	5. 4 ±7. 5%	0. 6	0. 0875	0. 6	0. 095	0. 6	0. 09
11	7. 35±7. 5%	0. 6	0. 0825	0. 6	0. 09	0. 6	0. 09
12	10. 5 ±7. 5%	0. 6	0. 085	0. 6	0. 095	0. 5	0. 08
13	14. 5 ±7. 5%	0. 6	0. 075	1. 0	0. 12	0. 7	0. 10
14	22. 0 ±7. 5%	0. 7	0. 085	1. 5	0. 155	1. 0	0. 135
15	30. 0 ±7. 5%	0. 8	0. 095	1. 6	0. 16	0. 7	0. 11
16	40. 0 ±7. 5%	0. 9	0. 125	1. 8	0. 175	0. 7	0. 115
17	52. 5 ±7. 5%	---	---	1. 8	0. 18	0. 8	0. 12
18	70. 0 ±7. 5%	---	---	1. 6	0. 155	1. 2	0. 15
19	93. 0 ±7. 5%	---	---	1. 0	0. 135	1. 0	0. 125
20	124. 0 ±7. 5%	---	---	1. 1	0. 13	---	---
21	165. 0 ±7. 5%	---	---	1. 0	0. 105	---	---
E	70. 0 ±15%	0. 6	0. 0825	---	---	---	---
H	165. 0 ±15%	---	---	---	---	1. 1	0. 125

TABLE I-3.4-4

SUMMARY OF INTERMODULATION DATA: CONSTANT BANDWIDTH MULTIPLEX FOR DEVIATION RATIO OF 2

		All Other Channels: MI = 20		All Other Channels: MI = 2		All Other Channels: Center Frequency	
Channel		Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW
No.	Freq. (kc)						
1	16 ±2	3.8	0.43	5.5	0.76	6.2	1.0
2	24 ±2	4.0	0.47				
3	32 ±2	4.2	0.55				
4	40 ±2	3.8	0.48				
5	48 ±2	3.8	0.47				
6	56 ±2	5.0	0.70				
7	64 ±2	3.0	0.43	3.5	0.46	5.5	0.64
8	72 ±2	3.2	0.42				
9	80 ±2	3.8	0.43				
10	88 ±2	3.5	0.44				
11	96 ±2	3.2	0.44				
12	104 ±2	3.0	0.43	3.2	0.46	4.5	0.60
13	112 ±2	3.0	0.40				
14	120 ±2	3.2	0.45				
15	128 ±2	3.5	0.42				
16	136 ±2	3.0	0.42				
17	144 ±2	3.0	0.43	3.7	0.47	4.5	0.53
18	152 ±2	3.2	0.40				
19	160 ±2	3.5	0.46				
20	168 ±2	3.2	0.42				
21	176 ±2	3.2	0.41				

TABLE I-3.4-5
SUMMARY OF INTERMODULATION DATA: CONSTANT BANDWIDTH MULTIPLEX FOR DEVIATION RATIO OF 1, 2, AND 4

		Channel							
		No. 6 56 kc ±2 kc		No. 10 88 kc ±2 kc		No. 14 120 kc ±2 kc		No. 19 160 kc ±2 kc	
Search Channel	All Other Channels	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW
DR = 1	MI = 20	10.0	1.4	7.5	1.0	7.5	1.0	7.5	1.0
	MI = 1	10.0	1.6	9.0	1.6	11.0	2.2	9.5	1.5
	Center Frequency	13.0	1.6	12.0	1.4	9.0	1.1	8.5	1.1
DR = 2	MI = 20	5.0	0.70	3.5	0.44	3.2	0.45	3.5	0.46
	MI = 2	5.5	0.76	3.5	0.46	3.2	0.46	3.7	0.47
	Center Frequency	6.2	1.0	5.5	0.64	4.5	0.60	4.5	0.53
DR = 4	MI = 20	0.22	0.17	0.13	0.09	0.13	0.09	0.14	0.10
	MI = 4	1.2	0.16	0.75	0.09	0.70	0.10	0.65	0.10
	Center Frequency	1.5	0.20	1.1	0.13	1.0	0.13	1.0	0.12

TABLE I-3.4-6
SUMMARY OF INTERMODULATION DATA: COMBINATIONAL BANDWIDTH MULTIPLEX

Constant Bandwidth Channels:

MI = 20 ($f_{mod.}$ = 100 cps)

Channel		Search Channel DR = 2	
No.	Freq. (kc)	Peak-Peak % FBW	Max. rms % FBW
1	16±2	5.5	0.62
2	24±2	6.5	0.65
3	32±2	5.5	0.66
4	40±2	5.5	0.65
5	48±2	5.5	0.57
6	56±2	6.0	0.88
7	64±2	3.5	0.48
8	72±2	4.0	0.47
9	80±2	4.0	0.50
10	88±2	4.5	0.50
11	96±2	4.0	0.51
12	104±2	4.5	0.51
13	112±2	4.0	0.46
14	120±2	3.5	0.51
15	128±2	5.0	0.51
16	136±2	5.0	0.51
17	144±2	4.0	0.52
18	152±2	4.5	0.50
19	160±2	5.0	0.58
20	168±2	5.0	0.54
21	176±2	5.0	0.55

IRIG Channels:

$f_{mod.}$ = 0.1 Nominal or 5 cps whichever is larger

Channel		Search Channel DR = 5	
No.	Freq. (kc)	Peak-Peak % FBW	Max. rms % FBW
1	0.40	0.15	0.03
2	0.56	0.25	0.03
3	0.73	0.45	0.08
4	0.96	0.30	0.04
5	1.30	0.40	0.06
6	1.70	0.45	0.06
7	2.30	0.30	0.03
8	3.00	0.35	0.04
9	3.90	0.30	0.04
10	5.40	0.40	0.05
11	7.35	0.35	0.04
Effect of Addition of IRIG Channel No. 12			
11	7.35	0.35	0.05
12	10.5	0.15	0.04
1*	16±2	5.00	0.78

*Constant Bandwidth Channel No. 1

TABLE I-3.4-7
SUMMARY OF INTERMODULATION DATA: CONSTANT BANDWIDTH MULTIPLEX WITH VARIOUS SYSTEM MODIFICATIONS

Search Channel: DR = 2 All Other Channels: MI = 20

a. Subcarrier-Discriminator Output Filter

Channel		Constant Amplitude 42 db per octave		Constant Amplitude 18 db per octave	
No.	Freq. (kc)	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW
3	32 ±2	4.2	0.55	4.0	0.53
6	56 ±2	5.0	0.70	4.8	0.63
19	160 ±2	3.5	0.46	3.5	0.49

b. RF Link

Channel		Complete System		No RF Link	
No.	Freq. (kc)	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW
6	56 ±2	5.0	0.70	1.0	0.15

c. Receiver

Channel		Nems-Clarke 1455A		DEI TMR-2A	
No.	Freq. (kc)	Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW
6	56 ±2	5.0	0.70	5.5	0.69
10	88 ±2	3.5	0.44	3.8	0.48
14	120 ±2	3.2	0.45	3.8	0.48
19	160 ±2	3.5	0.46	3.2	0.48

TABLE I-3.4-8

SUMMARY OF INTERMODULATION DATA: CONSTANT BANDWIDTH MULTIPLEX FOR VARIOUS SYSTEM MODIFICATIONS WITH EMR 246A TRANSMITTER

Search Channel: DR = 2 All Other Channels: MI = 20

Description of Test Performed on Channel 6 (56 kc ±2 kc)	Peak-Peak % FBW	Max rms % FBW
a. Standard Intermodulation Test: With Leach FM200 replaced by EMR Model 246A Transmitter	4. 5	0. 67
b. Effect of IF Bandwidth: Nems-Clarke Model 1455A 500 kc IF replaced with Nems-Clarke Special Model 1703A 1. 0 mc IF Receiver.	4. 0	0. 59
c. Effect of Uncorrelated VCO Modulation: Test a with VCO's Modulated with Separate 100 cps Sources.	5. 0	0. 62
d. Error Due to Receiver Noise: Test a with only test channel in multiplex.	2. 5	0. 36
e. Effect Of Reduced Number of Channels: Test c with only channel 1 through 16 in multiplex.	2. 5	0. 30
f. Effect of Reduced Transmitter Deviation: Test c with total transmitter reduced to half normal level.	5. 0	0. 72

3.5 SIGNAL-TO-NOISE

3.5.1 Proportional-Bandwidth Basebands

System signal-to-noise performance was measured on several representative channels of each baseband. The performance was determined by selecting a receiver IF carrier-to-noise ratio and measuring the resulting subcarrier discriminator output signal-to-noise ratio. The subcarrier-to-noise ratio at the output of the discriminator band-pass input filter was also measured. To eliminate the noise content due to intermodulation products, the signal-to-noise test was repeated in each case with only the test channel in the multiplex. A block diagram of the test is contained in Figure I-3.5-1; the detailed test procedure and measured data is contained in Volume II, section 3.5. The data was taken with the maximum transmitter deviation allowed by the radiated-spectrum test and with the appropriate pre-emphasis schedule.

Table I-3.5-2 shows a summary of the signal-to-noise performance for the IRIG baseband. The data is shown for two cases, full multiplex and with only the test channel in the multiplex. In each case, a carrier-to-noise ratio was selected and the signal-to-noise ratio was measured at both the subcarrier discriminator input (subcarrier-to-noise ratio), and at the discriminator (signal-to-noise ratio). For the signal-to-noise ratio at the discriminator output, the data was taken for three cases of modulation: center frequency no modulation, static deviation to bandedge, and full-bandwidth modulation at the maximum intelligence rate for a deviation ratio of 5. In all cases of signal-to-noise ratio measurements, the ratio is rms-to-rms expressed in db.

The signal-to-noise performance of the IRIG baseband with a wide-band channel in the highest frequency position is shown in Table I-3.5-3. Additional data points taken at a later date to better specify the shape of the performance curve and to verify the original data are indicated with an asterisk. Table I-3.5-4 shows a summary of the data for the IRIG baseband at deviation ratios of 2 and 1. This data was taken with the test channel unmodulated at center frequency. The data with the test channel at bandedge and modulated was not taken because the additional information which would have been gained did not warrant the extra test time. This conclusion was based upon the data obtained on the IRIG baseband evaluation mentioned previously. Table I-3.5-5 contains a summary of the signal-to-noise performance of the expanded proportional baseband operating at a deviation ratio of 5. The signal-to-noise performance of the expanded baseband with the wideband channel is shown in Table I-3.5-6. Figure I-3.5-7 shows a plot of signal-to-noise performance of the highest-frequency channel in each baseband, including the wideband channel.

A generally used, conservative criterion for acceptable telemetry system performance requires that thereceiver and the subcarrier discriminator threshold at the same carrier-to-noise ratio. With reference to Figure I-3.5-7, at a carrier-to-noise ratio of 9 db (receiver threshold) the standard baseband output signal-to-noise ratio was 40 db, 12 db above the discriminator threshold level. The carrier-to-noise ratio was decreased to below 4 db to make the discriminators threshold. The additional 12 db of channel performance at and above receiver threshold is considered unnecessary for most applications and is due directly to the larger transmitter deivation and higher VCO levels allowed by the radiated-spectrum specification used in the evaluation program. Identical results were obtained with a wideband ±15% channel in the highest-frequency position of the IRIG multiplex.

With expansion of the IRIG baseband to include three additional channels, the radiated-spectrum specification required a reduction in the rms transmitter deviation. The receiver and subcarrier discriminators then thresholded at the same carrier-to-noise ratio, 9 db. This system's output signal-to-noise ratio at threshold was 28 db in the pre-emphasized channels and higher in the low-frequency channels where the 3.0 kc minimum peak deviation criterion applies.

Additional reduction in transmitter rms deviation necessitated by the addition of the wideband (±15%) channel in the highest-frequency position of the expanded baseband (as explained in the section on radiated spectrum) caused the pre-emphasized channels to suffer a 3-db performance degradation. Because of the 3.0 kc minimum peak deviation previously mentioned, those channels below 22.0 kc are unaffected and exhibit output signal-to-noise performance of approximately 35 db at receiver threshold.

In summary, due to the radiated-spectrum specification and IF bandwidth used, the IRIG baseband allows exceptional performance even with one wideband channel included. The expanded 21-channel baseband provides receiver and subcarrier discriminator threshold at the same carrier-to-noise ratio with a small performance degradation upon addition of a wideband channel.

3.5.2 Constant- and Combinational-Bandwidth Basebands

System signal-to-noise performance was measured on one channel from each group of the constant- or combinational-bandwidth baseband using an identical procedure as for the proportional-bandwidth baseband. Table I-3.5-8 is a summary of the signal-to-noise performance for the 21-channel constant-bandwidth multiplex. The data was taken with the test channel unmodulated at center frequency for both the full multiplex and the test channel only in the multiplex. Only small differences are noticed. The performance at signal-to-noise ratios below receiver threshold improved slightly with the removal of intermodulation products; however, at normal operating levels there was no improvement.

Channels 17 through 21, Group D, were removed from the constant-bandwidth multiplex and the multiplex level increased to its maximum within the limitations of the radiated-spectrum specification (section 3.3). As was discussed under pre-emphasis (section 3.2) with the receiver at threshold, $(S/N)_c$ equal to 9 db, the subcarrier-to-noise ratios in the remaining 16 constant-bandwidth channels increased approximately 6 db. A choice existed between evaluating a 16-channel multiplex or a 21-channel multiplex. The 21-channel baseband was selected for evaluation since it put a more severe stress upon the laboratory telemeter.

Table I-3.5-9 shows a summary of the signal-to-noise performance of the constant-bandwidth multiplex operated at deviation ratios of 1 and 4. This data was taken with the test channel unmodulated at center frequency and at bandedge, and modulated full bandwidth at nominal channel cutoff frequency. The data for deviation ratio of 2 is also included for comparison. Since for the IRIG multiplex, the data with full multiplex was seen to differ only slightly from that with the test channel only in the multiplex, no data was taken for the test-channel-only case with the expanded basebands. The difference between the signal-to-noise performance with the test channel unmodulated at center frequency and at bandedge is due to the discriminator bandpass input filter attenuation of the subcarrier signal. The subcarrier is attenuated approximately 2.5 db at full deviation. The performance difference between the modulated and unmodulated condition is due both to attenuation of the bandpass input filter and the characteristics of the phase-locked-loop discriminator. With no modulation there is no phase error in the phase-locked loop; however, full-bandwidth modulation at nominal cutoff produces approximately 45° peak phase error, or almost half the available phase range, before loss of lock occurs. Thus, with the addition of noise the discriminator has a greater probability of losing lock than with no modulation. Hence, the signal-to-noise performance is degraded.

The signal-to-noise performance of the combinational-bandwidth multiplex is summarized in Table I-3.5-10. The improvement in performance of the constant-bandwidth channels with the addition of the IRIG channels (as described in the radiated-spectrum section) is apparent. As expected, the performance of the IRIG channels was virtually identical to their performance in the IRIG proportional-bandwidth baseband shown in Table I-3.5-2. The performance of the combinational-bandwidth multiplex with the test channel modulated and at bandedge is summarized in Table I-3.5-11.

Figure I-3.5-12 is a plot of the signal-to-noise performance of both the constant- and combinational-bandwidth basebands. The figure shows the performance of constant-bandwidth channels 6 and 19 for both basebands and IRIG channel 8 for the combinational-bandwidth basebands. The dotted line shows the carrier-to-noise ratio at which the receiver thresholds. The point where the subcarriers threshold is not shown because two different deviation ratios are involved--deviation ratio of 2 for the constant-bandwidth channels and 5 for the IRIG channels. The detailed test procedures and the measured data for the signal-to-noise test are contained in section 3.5 of Volume II.

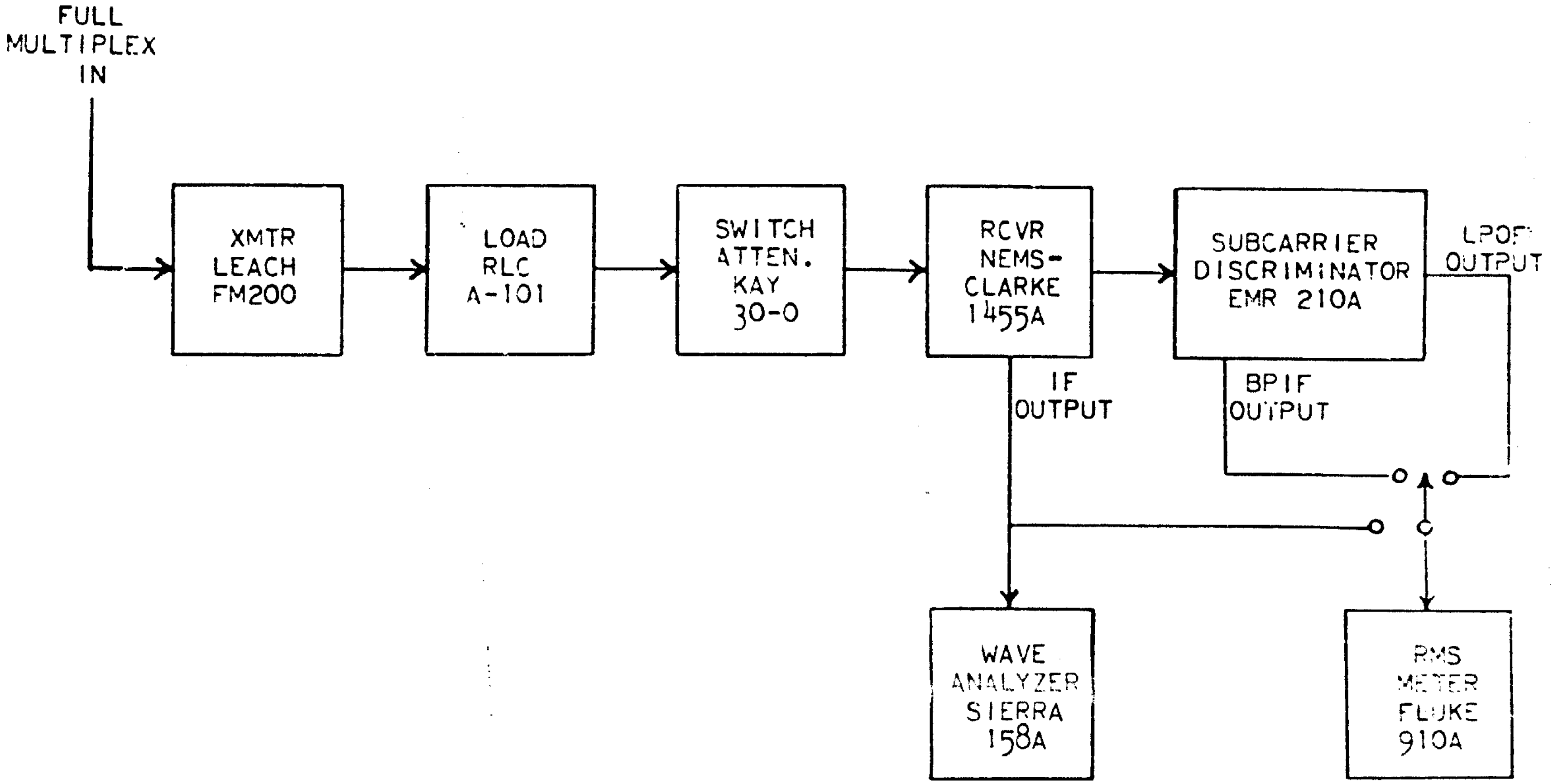


FIGURE I-3.5-1
SIGNAL-TO-NOISE TEST BLOCK DIAGRAM

TABLE I-3.5-2
SUMMARY OF SIGNAL-TO-NOISE DATA: IRIG 18-CHANNEL MULTIPLEX, DEVIATION RATIO OF 5

		Full Multiplex				Test Channel Only			
			$(S/N)_d$				$(S/N)_d$		
Channel Frequency (kc)	$(S/N)_c$ (db)	$(S/N)_s$ (db)	CF (db)	LBE (db)	Mod. at f_m (db)	$(S/N)_s$ (db)	CF (db)	LBE (db)	Mod. at f_m (db)
70 kc ± 7.5%	2	8.0	17.7	9.33	11.3	8.9	17.7	9.1	14.5
	4	12.4	30.7	22.8	31.6	12.9	31.6	25.9	31.6
	6	16.6	34.1	31.0	32.6	16.9	35.4	35.4	34.8
	9	21.1	40.4	40.8	39.9	21.7	41.4	42.0	40.6
	14	25.3	45.4	45.9	45.7	27.2	46.0	47.4	45.0
3.0 kc ± 7.5%	2	3.0	8.4	2.85	4.00	5.0	12.[illegible]	4.44	4.65
	4	8.0	25.9	11.3	27.5	9.5	29.6	21.9	28.9
	6	11.8	29.3	28.8	29.3	17.4	34.4	[illegible].1	[illegible].9
	9	20.0	41.6	41.0	41.3	29.5	52.0	51.8	49.2
	14	20.7	54.4	52.7	49.6	34.7	61.3	6[illegible].8	52.4

TABLE I-3.5-3
SUMMARY OF SIGNAL-TO-NOISE DATA: IRIG MULTIPLEX, CHANNELS 1 THROUGH 16 AND E, DEVIATION RATIO OF 5

		Full Multiplex				Test Channel Only			
			$(S/N)_d$				$(S/N)_d$		
Center Frequency (kc)	$(S/N)_c$ (db)	$(S/N)_s$ (db)	CF (db)	LBE (db)	Mod. at f_m (db)	$(S/N)_s$ (db)	CF (db)	LBE (db)	Mod. at f_m (db)
3.00 ±7.5%	14	19.5	53.5	52.4	45.0	26.5	57.9	57.0	50.1
	9	17.7	37.2	37.9	34.7	19.2	45.9	46.9	42.3
	4	4.4	11.9	5.0	3.4	4.9	23.0	7.4	6.4
70.0 ±15%	14	27.0	45.9	45.9	39.2	27.0	46.4	46.4	39.4
	9	21.5	37.3	39.6	35.7	21.5	38.9	40.1	36.2
	4	11.9	22.3	15.4	14.1	11.9	22.3	15.4	14.1
* Rechecked data	11 *	24.3	43.6	---	---	24.6	44.1	---	---
	6 *	17.6	35.8	---	---	18.2	36.9	---	---
	4 *	12.8	30.1	---	---	13.5	31.0	---	---
	2 *	8.8	18.8	---	---	9.4	19.4	---	--

TABLE I-3.5-4
SUMMARY OF SIGNAL-TO-NOISE DATA: IRIG MULTIPLEX, DEVIATION RATIOS OF ONE AND TWO

		Full Multiplex			Test Channel Only		
Channel Frequency	$(S/N)_c$ (db)	$(S/N)_s$ (db)	$(S/N)_d$ DR = 2 (db)	$(S/N)_d$ DR = 1 (db)	$(S/N)_s$ (db)	$(S/N)_d$ DR = 2 (db)	$(S/N)_d$ DR = 1 (db)
960 cps ±7.5%	2	3.5	7.4	3.9	5.5	9.0	5.0
	4	9.0	16.2	10.1	12.0	19.5	14.1
	9	22.0	31.9	26.1	35.0	43.0	38.7
	14	24.2	43.9	34.7	38.2	54.7	50.1
3.0 kc ±7.5%	2	3.0	5.0	1.4	5.0	7.4	3.0
	4	7.5	14.1	9.0	11.5	17.9	12.4
	9	21.0	31.0	23.9	35.0	42.2	37.0
	14	23.2	41.4	32.4	41.2	54.1	50.1
7.35 kc ±7.5%	2	2.0	5.0	0.7	3.5	6.1	2.0
	4	7.0	12.9	7.4	10.0	17.9	11.9
	9	22.5	29.0	23.0	32.5	39.5	33.5
	14	30.5	40.1	34.7	40.9	49.8	44.8
22.0 kc ±7.5%	2	4.1	6.9	2.7	5.5	9.4	4.5
	4	6.2	11.0	6.9	9.7	17.0	10.1
	9	24.0	31.4	25.0	30.2	37.3	31.1
	14	29.4	38.4	32.4	35.7	45.0	37.0
70.0 kc ±7.5%	2	7.4	7.4	5.9	8.4	10.1	7.2
	4	12.9	18.4	11.9	14.7	20.7	14.1
	9	21.3	28.7	22.3	22.7	29.8	23.9
	14	25.3	34.1	27.4	28.1	35.4	29.4

TABLE I-3.5-5
SUMMARY OF SIGNAL-TO-NOISE DATA: EXPANDED PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 THROUGH 21, DEVIATION RATIO OF 5

Channel	Frequency (kc)	$(S/N)_c$ (db)	Full Multiplex		Test Channel Only	
			$(S/N)_s$ (db)	$(S/N)_d$ (db)	$(S/N)_s$ (db)	$(S/N)_d$ (db)
8	3.00± 7.5%	19	17.9	54.7	29.9	60.1
		14	17.8	51.4	32.1	57.9
		9	14.5	34.7	21.3	41.2
		4	1.4	6.4	2.8	9.4
18	70.0± 7.5%	19	17.6	38.3	19.7	38.7
		14	14.2	33.5	15.1	34.1
		9	9.0	27.1	10.1	28.5
		4	1.7	6.4	3.0	8.4
19	93.0± 7.5%	19	22.1	42.1	23.0	42.7
		14	18.2	37.7	18.6	38.1
		9	13.1	31.7	13.3	32.4
		4	4.9	11.4	5.7	14.1
20	124±7.5%	19	18.4	38.1	19.5	38.5
		14	14.8	33.5	15.1	34.1
		9	9.8	28.7	9.8	28.5
		4	3.6	8.7	4.0	10.6
21	165±7.5%	19	19.0	38.3	19.0	38.7
		14	14.5	33.7	14.4	34.1
		9	9.5	28.7	9.2	28.5
	* Data rechecked	4	3.8	10.6	3.8	11.9
		11 *	---	---	11.1	30.1
		6 *	---	---	7.6	23.9

TABLE I-3.5-6
SUMMARY OF SIGNAL-TO-NOISE DATA: EXPANDED PROPORTIONAL BANDWIDTH MULTIPLEX, CHANNELS 1 THROUGH 19 AND H DEVIATION RATIO OF 5

Channel	Frequency (kc)	$(S/N)_c$ (db)	Full Multiplex		Test Channel Only	
			$(S/N)_s$ (db)	$(S/N)_d$ (db)	$(S/N)_s$ (db)	$(S/N)_d$ (db)
8	3.0±7.5%	19	18.1	55.7	29.1	61.1
		14	17.4	51.9	27.9	56.6
		9	15.7	37.0	21.7	43.4
		4	3.9	10.1	6.3	15.4
18	70.0±7.5%	19	16.4	35.7	17.1	36.0
		14	12.0	30.8	12.2	31.0
		9	7.3	24.5	7.5	25.4
		4	2.1	7.4	2.9	9.4
19	93.0±7.5%	19	16.5	41.7	16.7	41.9
		14	11.9	36.8	11.9	37.0
		9	7.4	26.9	7.2	29.4
		4	2.9	13.5	3.1	14.6
H	165±15%	19	16.6	35.3	16.6	35.8
		14	11.9	30.6	11.9	31.0
		9	7.4	23.7	7.3	24.1
		4	3.5	9.8	3.3	10.1
	* Data rechecked	11 *	---	---	9.3	28.4
		6 *	---	---	4.9	13.9

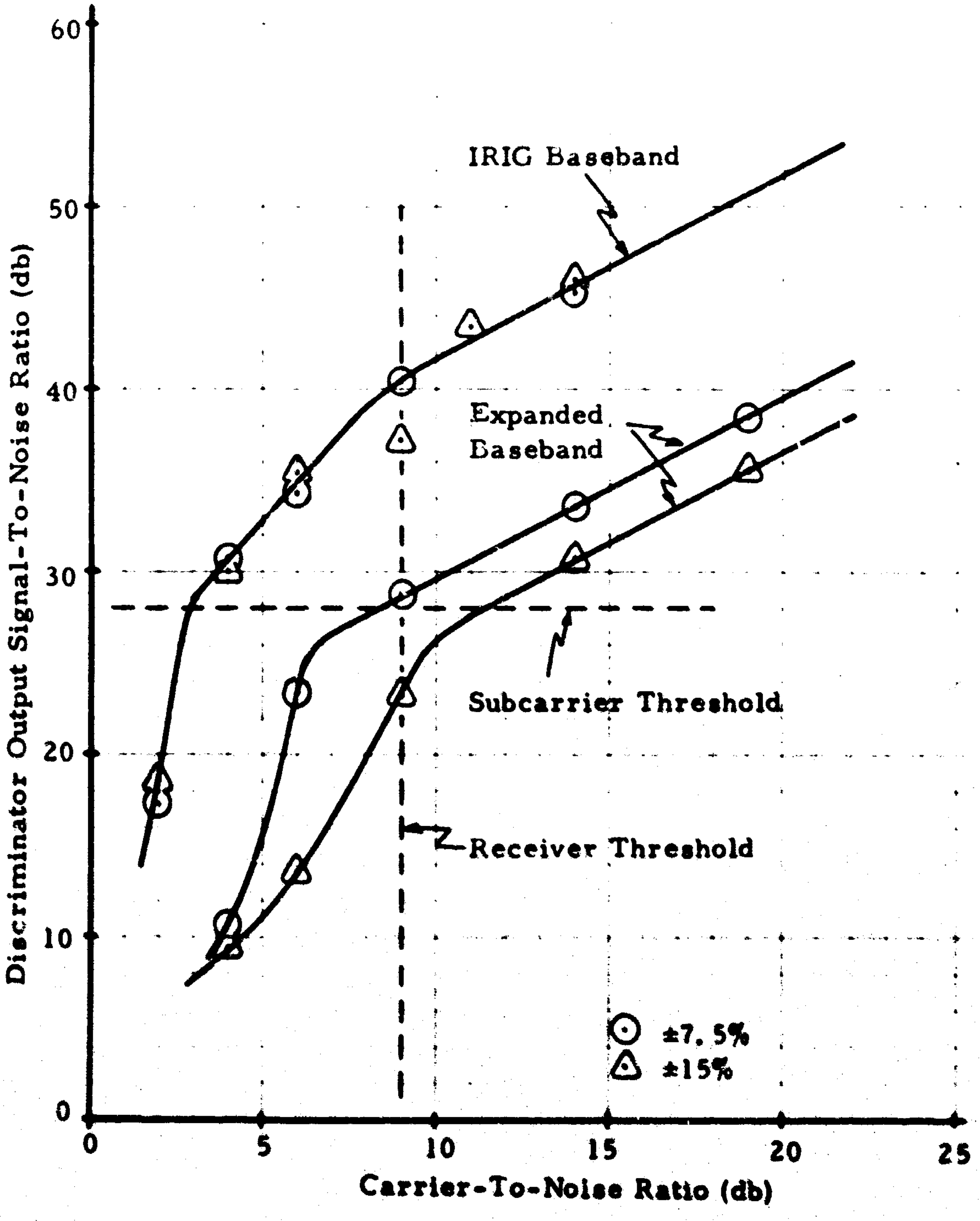


FIGURE I-3.5-7
SIGNAL-TO-NOISE PERFORMANCE OF HIGH FREQUENCY CHANNEL IN EACH PROPORTIONAL BANDWIDTH BASEBAND, DEVIATION RATIO OF 5

TABLE I-3.5-8
SUMMARY OF SIGNAL-TO-NOISE DATA: CONSTANT BANDWIDTH MULTIPLEX FOR DEVIATION RATIO OF 2

		Full Multiplex		Test Channel Only	
Channel	$(S/N)_c$ (db)	$(S/N)_s$ (db)	$(S/N)_d$ (db)	$(S/N)_s$ (db)	$(S/N)_d$ (db)
No. 6 56 kc ±2 kc	6	2.1	2.2	2.4	2.6
	9	5.1	8.0	5.1	8.0
	12	7.5	12.5	7.5	12.5
	15	10.0	16.9	10.0	17.0
	18	13.4	20.7	13.5	20.7
	21	15.6	23.1	15.8	23.1
	24	18.7	27.0	19.2	27.0
No. 10 88 kc ±2 kc	6	2.4	3.2	2.4	3.4
	9	5.1	9.0	5.1	9.0
	12	7.4	13.5	7.4	13.5
	15	9.7	17.6	9.8	17.7
	18	12.9	21.3	12.9	21.3
	21	15.3	23.5	15.5	23.7
	24	18.5	27.1	18.9	27.4
No. 14 120 kc ±2 kc	6	2.7	3.1	2.7	3.1
	9	5.2	8.5	5.2	8.5
	12	7.3	13.5	7.3	13.5
	15	9.6	16.8	9.6	16.9
	18	12.9	20.6	13.0	20.6
	21	15.1	23.0	15.3	23.1
	24	18.3	26.3	18.6	26.6
No. 19 160 kc ±2 kc	6	3.0	3.7	3.0	3.7
	9	4.4	9.2	4.4	9.2
	12	7.5	14.0	7.5	14.0
	15	9.7	17.3	9.7	17.3
	18	13.0	20.9	13.1	21.1
	21	15.3	23.1	15.3	23.4
	24	18.4	26.6	18.8	26.8

TABLE I-3.5-9

SUMMARY OF SIGNAL-TO-NOISE DATA: CONSTANT-BANDWIDTH MULTIPLEX; CHANNEL 14 (Full Multiplex Case Only); DEVIATION RATIOS OF 1, 2, AND 4

	DR = 1				DR = 2				DR = 4			
$(S/N)_c$ (db)	$(S/N)_s$ (db)	$(S/N)_d$ (db)			$(S/N)_s$ (db)	$(S/N)_d$ (db)			$(S/N)_s$ (db)	$(S/N)_d$ (db)		
		CF	HBE	Mod.		CF	HBE	Mod.		CF	HBE	Mod.
6	2.4	-1.1	-3.3	-3.0	2.3	3.1	0.4	1.2	2.5	5.6	2.0	0.7
9	4.7	2.4	2.0	0.0	4.7	8.5	1.0	2.2	4.8	9.0	3.8	5.5
12	7.2	6.8	1.9	4.7	7.3	13.5	5.6	7.9	7.1	19.8	8.5	11.5
15	9.3	10.0	6.8	9.0	9.5	16.8	12.5	14.0	9.4	28.0	17.2	20.0
18	12.6	13.9	11.9	13.3	12.8	20.6	20.5	21.0	12.8	32.5	32.5	32.0
21	14.8	16.3	14.0	15.6	15.3	23.0	23.1	23.6	15.1	34.9	34.9	33.9
24	17.1	19.3	17.2	18.0	18.5	26.3	26.5	27.0	16.4	38.4	38.6	36.5

TABLE I-3.5-10
SUMMARY OF SIGNAL-TO-NOISE DATA: COMBINATIONAL BANDWIDTH MULTIPLEX FOR DEVIATION RATIO OF 2

		Full Multiplex		Test Channel Only	
Channel	$(S/N)_c$ (db)	$(S/N)_s$ (db)	$(S/N)_d$ (db)	$(S/N)_s$ (db)	$(S/N)_d$ (db)
No. 8 3.0 kc ±7.5%	6	10.2	29.7	13.5	32.2
	9	20.1	42.0	28.6	47.5
	12	22.0	49.7	38.2	56.6
	15	22.5	56.3	41.5	59.5
	18	22.5	58.0	41.9	59.9
	21	22.6	58.0	41.8	60.0
	24	22.7	58.0	41.2	60.0
No. 6 56 kc ±2 kc	6	3.1	4.0	4.5	5.6
	9	8.0	14.0	8.8	15.5
	12	11.1	18.6	11.6	18.8
	15	14.0	21.5	14.1	21.7
	18	17.4	25.1	17.8	25.4
	21	19.5	27.5	20.2	27.8
	24	22.0	30.5	23.5	31.3
No. 10 88 kc ±2 kc	6	4.2	6.7	4.9	8.5
	9	8.5	15.8	8.8	16.6
	12	11.2	19.2	11.2	19.6
	15	12.8	22.0	13.8	22.3
	18	17.2	25.7	17.4	26.0
	21	19.3	27.9	19.7	28.5
	24	22.0	31.0	23.0	32.0
No. 14 120 kc ±2 kc	6	4.8	6.5	4.8	7.7
	9	8.5	14.2	8.5	14.8
	12	11.2	17.4	11.2	17.7
	15	13.5	20.0	13.5	20.2
	18	17.0	23.7	17.2	23.9
	21	19.2	25.9	19.6	26.3
	24	22.0	29.0	23.1	29.8
No. 19 160 kc ±2 kc	6	5.5	7.8	5.2	8.5
	9	8.8	14.4	8.5	15.0
	12	11.2	17.4	11.2	18.0
	15	13.7	20.1	13.7	20.5
	18	17.0	23.6	17.2	24.3
	21	19.0	25.8	19.5	26.5
	24	21.8	28.9	23.3	29.9

TABLE I-3.5-11
SUMMARY OF SIGNAL-TO-NOISE DATA: COMBINATIONAL BANDWIDTH MULTIPLEX; EFFECT OF TEST CHANNEL DEVIATION; CHANNELS 8 AND 14
(Full Multiplex Case Only)

			$(S/N)_d$ (db)		
Channel	$(S/N)_c$ (db)	$(S/N)_s$ (db)	CF	HBE	Mod at f_m
No. 8 3.0 kc ±7.5% DR = 5	6	10.2	29.7	30.0	31.0
	9	20.1	42.0	42.0	41.0
	12	22.0	49.7	50.5	46.5
	15	22.5	56.3	55.2	48.0
	18	22.5	58.0	56.0	48.0
	21	22.6	58.0	56.0	48.0
	24	22.7	58.0	56.0	48.2
No. 14 120 kc ±2 kc DR = 2	6	4.8	6.5	0.5	2.8
	9	8.5	14.2	9.2	11.0
	12	11.2	17.4	15.8	18.0
	15	13.5	20.0	20.0	22.0
	18	17.0	23.7	24.3	25.4
	21	19.2	25.9	26.6	27.6
	24	22.0	29.0	29.8	30.5

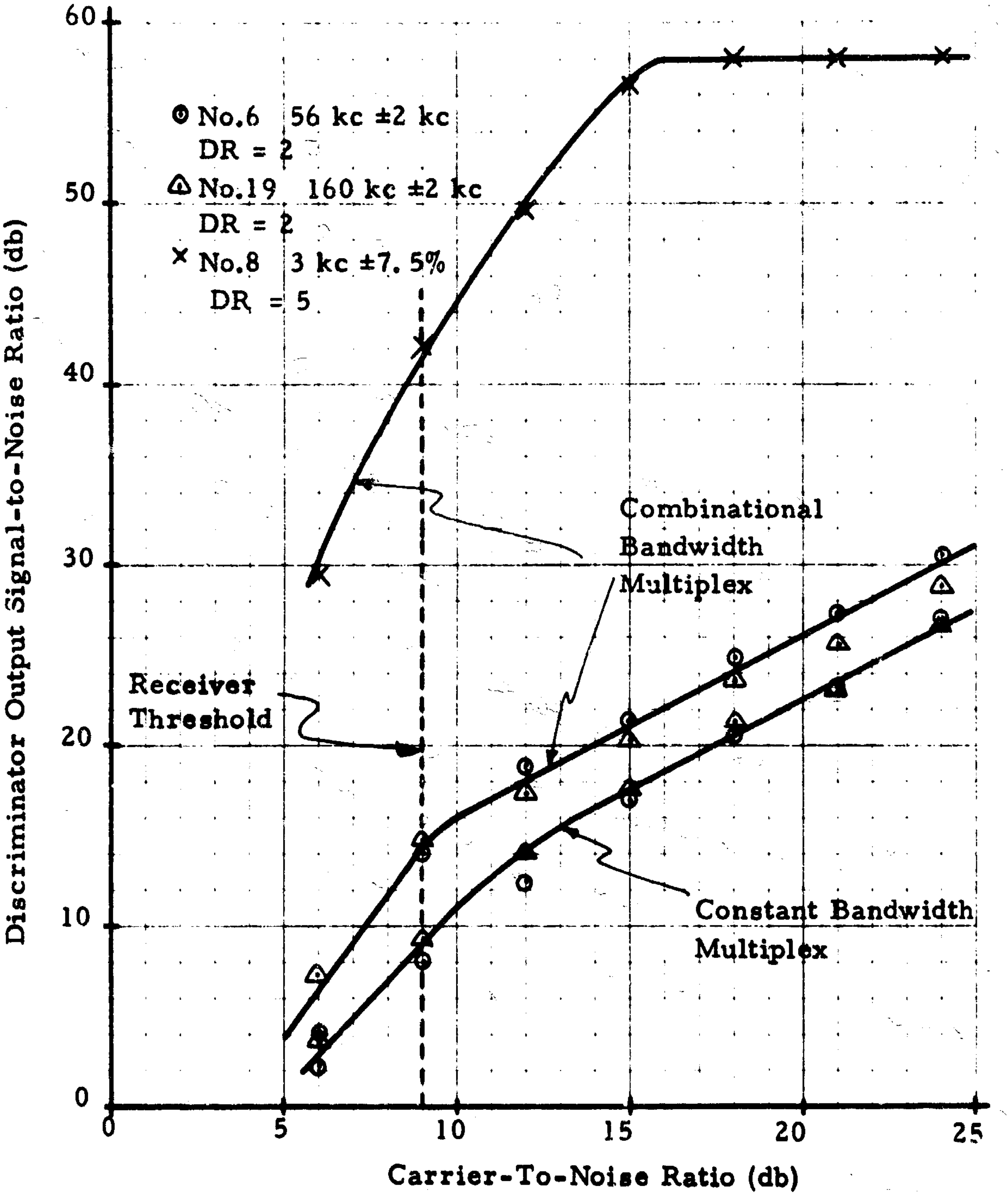


FIGURE I-3.5-12
SIGNAL-TO-NOISE PERFORMANCE OF CONSTANT AND
COMBINATIONAL BANDWIDTH BASEBANDS

3.6 SYSTEM ERROR

In essence, the system-error test uses a null technique, as shown in the block diagram of Figure I-3.6-1, to measure the difference between the system input and the system output. The components in the output that are not removed by nulling with the input signal constitute the error voltage; both the peak-to-peak and rms levels are measured and converted to percent of full bandwidth. These errors are primarily due to harmonic distortion, filter attenuation, and receiver noise. For each baseband evaluated, representative channels are selected for the system-error test.

The test was conducted at a carrier-to-noise ratio of 39 db with all channels except the channel under test deviated full bandwidth at their maximum rate. The test channel's input and output were compared at three positions in the data channel: 0.3, 0.5, and 1.0 times the nominal cutoff frequency, f_m, of the channel. In each case the test was run with an amplitude and phase null at the 0.3 f_m position. With increase in frequency to 0.5 f_m and 1.0 f_m, the only adjustment allowed in the test was a phase adjustment to compensate for phase shifts through the system. The test was then repeated with both phase and amplitude adjustments at each position in the data passband. In this way, the effects of filter attenuation were determined. To isolate the effects of intermodulation, the test was repeated with only the test channel in the multiplex.

The system-error test data for the IRIG proportional-bandwidth baseband, channels 1 through 18, is summarized in Tables I-3.6-2 and I-3.6-3. This data includes operation at deviation ratios of 1, 2, and 5. The data for the IRIG baseband with a wideband channel, as well as the data for the expanded proportional-bandwidth basebands, is summarized in Tables I-3.6-4 and I-3.6-5.

The total system error with either of the proportional-bandwidth basebands was found to be equal to or less than 2% of full bandwidth for system operation at a carrier-to-noise ratio of 39 db. Operating the system with a wideband (±15%) channel in the highest frequency position in either baseband gave similar results. Reducing the deviation ratio on the IRIG baseband to 2 and 1 produced system errors equal to or less than 2% and 5% of full bandwidth, respectively. The maximum error was found at cutoff frequency and is attributed to amplitude rolloff in the subcarrier discriminator low-pass output filter. In all cases, this output filter was a constant-amplitude, 18-db-per-octave type. If an amplitude correction is allowed, the system error reduces to less than 0.5% of full bandwidth for the basebands operated with a deviation ratio of 5. For the IRIG baseband operated at deviation ratios of 2 and 1, the error reduces to less than 0.7% and 1.8% of full bandwidth, respectively, with the amplitude correction. By deleting all channels except the channel under test from the multiplex, the contribution of intermodulation products to system error was removed. On the high-frequency channels, the intermodulation was found to be negligible; however, on the low channels, approximately half the system error was found to be due to intermodulation when the effect of amplitude error is also removed. For the case of deviation ratios less than 5, the system error with amplitude error removed was found to be predominantely due to intermodulation.

The system-error data for the constant-bandwidth multiplex is summarized in Tables I-3.6-6 and I-3.6-7. Like the proportional-bandwidth basebands, the maximum error occurs at channel cutoff due to the output filter attenuation. Intermodulation contributes to the system error in the low-frequency channels only, and is partially masked by the output-filter-attenuation error.

Figures I-3.6-8 and I-3.6-9 summarize the system-error data for the combinational-bandwidth multiplex. The error in the constant-bandwidth channels is slightly higher with the combinational multiplex compared to the same channel's performance in the constant-bandwidth multiplex. Also, intermodulation contributes slightly more error than before. This effect was also seen in the intermodulation test of section 3.4. The system error for IRIG channel 8 is comparable to the same channel's performance in the IRIG multiplex.

The detailed procedure for the system-error test as well as the measured data is contained in section 3.5 of Volume II.

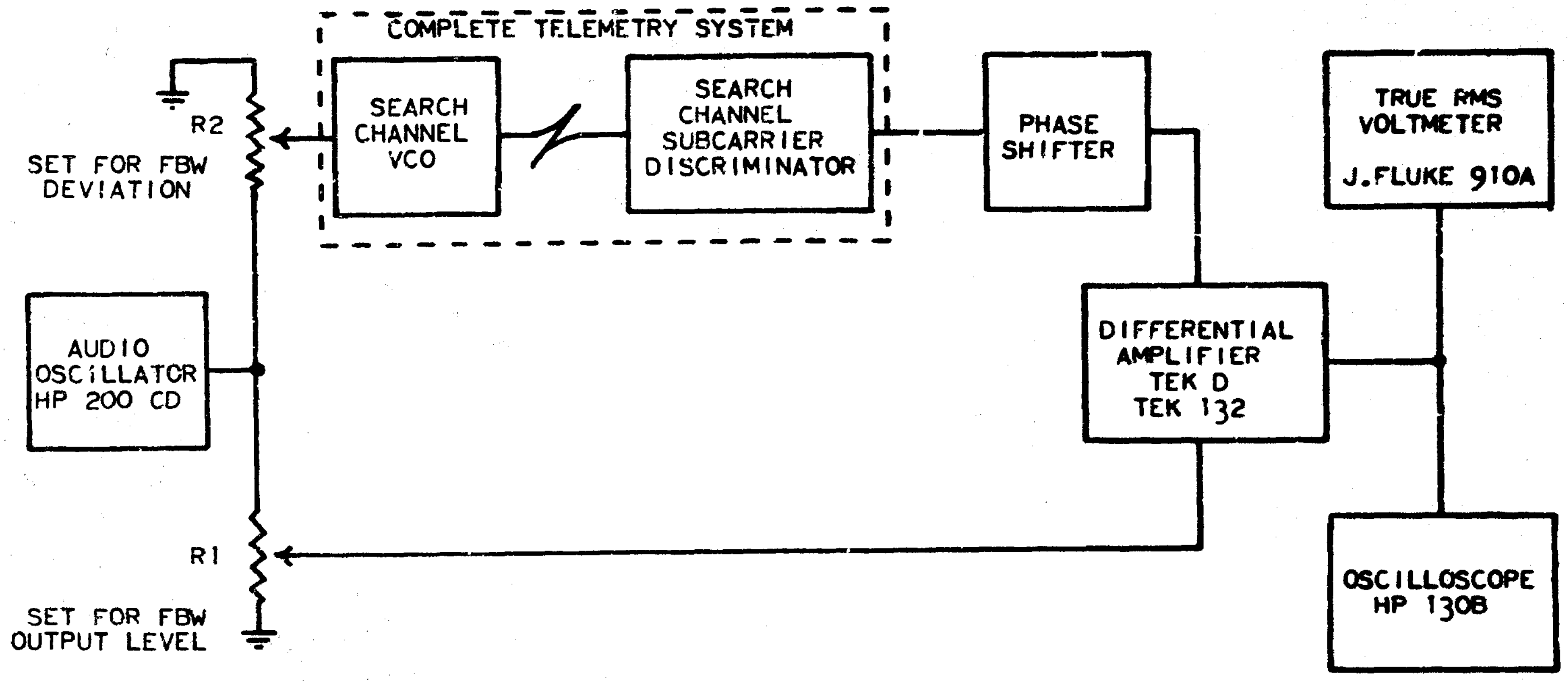


FIGURE I-3.6-1
SYSTEM ERROR TEST BLOCK DIAGRAM

TABLE I-3.6-2
SUMMARY OF SYSTEM ERROR DATA: IRIG BASEBAND, CHANNELS 1 THROUGH 18

Data Frequency		$0.3\ f_m$				$0.5\ f_m$				$1.0\ f_m$			
		Phase Null Only		Phase and Amplitude Null		Phase Null Only		Phase and Amplitude Null		Phase Null Only		Phase and Amplitude Null	
Channel (kc)	Dev. Ratio	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW
70 ± 7.5%	5	0.15	0.8	0.15	0.8	0.8	1.0	0.2	1.0	2.0	6.2	0.15	1.0
	2	0.42	4.0	0.42	4.0	0.94	5.0	0.53	4.5	1.9	10.0	0.47	4.5
	1	1.22	12.0	1.22	12.0	4.9	25.0	1.3	10.0	1.18	12.0	1.18	9.0
22 ± 7.5%	2	0.32	1.5	0.32	1.5	1.43	5.0	0.7	3.0	2.0	7.0	0.5	2.5
	1	0.67	5.0	0.67	5.0	4.8	17.0	1.36	6.0	1.32	6.0	0.85	4.0
7.35 ± 7.5%	2	0.34	3.0	0.34	3.0	1.35	7.0	0.7	4.0	1.62	7.0	0.6	3.5
	1	0.71	5.0	0.71	5.0	5.1	20.0	1.65	10.0	1.85	10.0	1.0	6.0
3.0 ± 7.5%	5	0.16	0.6	0.16	0.6	0.17	0.6	0.16	0.6	1.9	5.8	0.1	0.4
	2	0.43	3.0	0.43	3.0	1.26	4.0	0.5	2.0	1.48	6.0	0.42	2.5
	1	1.8	15.0	1.8	15.0	4.3	20.0	1.6	8.0	4.1	15.0	1.45	6.0
0.96 ± 7.5%	2	0.33	4.0	0.33	4.0	1.25	5.0	0.37	3.5	1.35	6.0	0.37	3.0
	1	1.4	16.0	1.4	16.0	4.1	20.0	1.3	12.0	3.5	16.0	1.2	10.0

TABLE I-3.6-3
SUMMARY OF SYSTEM ERROR DATA: IRIG BASEBAND, CHANNELS 1 THROUGH 18, TEST CHANNEL ONLY

Data Frequency		0.3 f_m				0.5 f_m				1.0 f_m			
		Phase Null Only		Phase and Amplitude Null		Phase Null Only		Phase and Amplitude Null		Phase Null Only		Phase and Amplitude Null	
Channel (kc)	Dev. Ratio	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW
70 ± 7.5%	5	0.12	0.5	0.12	0.5	0.18	0.6	0.18	0.8	2.0	5.8	0.12	0.5
	2	0.14	0.8	0.14	0.8	0.85	3.2	0.37	1.8	1.86	6.0	0.25	1.2
	1	0.15	1.2	0.15	1.2	4.8	16.0	0.76	3.5	0.18	1.2	0.18	1.4
22 ± 7.5%	2	0.15	0.6	0.15	0.6	1.4	5.0	0.58	2.0	2.0	6.0	0.41	1.5
	1	0.15	0.6	0.15	0.6	4.75	15.0	1.21	4.5	0.98	3.0	0.45	1.5
7.35 ± 7.5%	2	0.17	0.9	0.17	0.9	1.3	5.0	0.57	2.0	1.54	5.0	0.51	2.0
	1	0.16	0.9	0.16	0.9	5.0	16.0	1.44	6.5	1.75	5.8	0.45	2.0
3.0 ± 7.5%	5	0.14	0.5	0.14	0.5	0.15	0.5	0.14	0.5	1.9	5.8	0.08	0.4
	2	0.13	0.6	0.13	0.6	1.2	3.6	0.32	1.3	1.43	4.8	0.18	0.75
	1	0.18	0.8	0.18	0.8	4.1	15.0	0.7	3.0	3.8	12.0	0.25	1.0
0.96 ± 7.5%	2	0.17	0.9	0.17	0.9	1.2	4.0	0.2	1.0	1.25	4.5	0.17	0.8
	1	0.16	0.8	0.16	0.8	4.0	13.2	0.48	2.0	3.35	10.0	0.23	1.4

TABLE I-3.6-4
SUMMARY OF SYSTEM ERROR DATA: PROPORTIONAL BANDWIDTH MULTIPLEXES

Data Frequency		$0.3 f_m$				$0.5 f_m$				$1.0 f_m$			
		Phase Null Only		Phase and Amplitude Null		Phase Null Only		Phase and Amplitude Null		Phase Null Only		Phase and Amplitude Null	
Channel (kc)	Dev. Ratio	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW
Baseband: Channels 1 through 16 and E													
70.0 ±15%	5	0.29	1.25	0.29	1.25	0.41	1.50	0.41	1.50	1.14	3.80	0.33	1.40
3.0 ±7.5%	5	0.145	0.70	0.145	0.70	0.165	0.70	0.155	0.60	1.16	3.60	0.085	0.40
Baseband: Channels 1 through 21													
165.0±7.5%	5	0.13	1.00	0.13	1.00	0.165	1.40	0.155	1.10	1.65	5.50	0.15	1.10
124.0±7.5%	5	0.18	1.20	0.18	1.20	0.29	1.60	0.21	1.40	0.81	3.50	0.165	1.20
93.0±7.5%	5	0.144	1.00	0.144	1.00	0.29	1.60	0.19	1.00	0.83	3.00	0.16	1.00
70.0±7.5%	5	0.16	1.40	0.16	1.40	0.24	1.60	0.15	1.20	0.82	3.50	0.14	1.00
3.0 ±7.5%	5	0.12	0.70	0.12	0.70	0.16	0.80	0.125	0.70	1.00	3.25	0.09	0.50
Baseband: Channels 1 through 19 and H													
165 ±15.0%	5	0.175	1.20	0.175	1.20	0.215	1.40	0.20	1.20	1.50	5.00	0.14	1.00
93.0±7.5%	5	0.17	1.20	0.17	1.20	0.32	1.80	0.22	1.20	0.92	3.50	0.18	1.20
70.0±7.5%	5	0.13	1.00	0.13	1.00	1.07	4.00	0.15	1.10	2.12	7.00	0.124	0.90
3.00±7.5%	5	0.13	0.80	0.13	0.80	0.20	1.00	0.15	0.90	0.95	3.50	0.10	0.60

TABLE I-3.6-5
SUMMARY OF SYSTEM ERROR DATA: PROPORTIONAL BANDWIDTH MULTIPLEXES, TEST CHANNEL ONLY

Data Frequency		$0.3 f_m$				$0.5 f_m$				$1.0 f_m$			
		Phase Null Only		Phase and Amplitude Null		Phase Null Only		Phase and Amplitude Null		Phase Null Only		Phase and Amplitude Null	
Channel (kc)	Dev. Ratio	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW
Multiplex: Channels 1 through 16 and E													
70.0±15%	5	0.28	1.00	0.28	1.00	0.40	1.30	0.40	1.30	1.14	3.60	0.32	1.20
3.00±7.5%	5	0.13	0.60	0.13	0.60	0.16	0.60	0.15	0.60	1.16	3.70	0.075	0.30
Multiplex: Channels 1 through 21													
165±7.5%	5	0.105	0.70	0.105	0.70	0.15	0.90	0.14	0.80	1.64	5.20	0.13	0.80
124±7.5%	5	0.15	0.80	0.15	0.80	0.27	1.40	0.18	1.00	0.80	2.75	0.13	0.80
93.0±7.5%	5	0.122	0.70	0.122	0.70	0.28	1.20	0.17	0.80	0.83	2.75	0.13	0.70
70.0±7.5%	5	0.11	0.80	0.11	0.80	0.22	1.00	0.11	0.60	0.80	2.75	0.09	0.60
3.00±7.5%	5	0.095	0.60	0.095	0.60	0.14	0.70	0.11	0.60	1.00	3.25	0.07	0.40
Multiplex: Channels 1 through 19 and E													
165±15%	5	0.1	1.20	0.17	1.20	0.20	1.20	0.165	1.10	1.50	5.00	0.13	0.90
93.0±7.5%	5	0.15	1.00	0.15	1.00	0.31	1.40	0.20	1.00	0.92	3.00	0.16	1.00
70.0±7.5%	5	0.10	0.70	0.10	0.70	1.05	3.50	0.125	0.80	2.12	6.50	0.095	0.60
3.00±7.5%	5	0.12	0.50	0.12	0.50	0.19	0.90	0.14	0.70	0.95	3.00	0.09	0.50

TABLE I-3.6-6
SUMMARY OF SYSTEM ERROR DATA: CONSTANT BANDWIDTH MULTIPLEX

Data Frequency	$0.3\ f_m$				$0.5\ f_m$				$1.0\ f_m$			
	Phase Null Only		Phase and Amp Null		Phase Null Only		Phase and Amp Null		Phase Null Only		Phase and Amp Null	
Channel (kc)	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW
No. 6 56 kc ±2 kc	0.55	4.5	0.55	4.5	1.4	7.6	1.3	7.0	2.4	10.0	0.48	4.0
No. 10 88 kc ±2 kc	0.45	3.0	0.45	3.0	1.5	7.5	1.1	5.0	1.9	7.0	0.37	2.8
No. 14 120 kc ±2 kc	0.57	3.5	0.57	3.5	1.8	7.4	1.6	7.5	2.4	8.5	0.35	2.5
No. 19 160 kc ±2 kc	0.62	4.0	0.62	4.0	2.0	8.0	1.8	8.0	1.9	7.0	0.34	2.5

TABLE I-3.6-7
SUMMARY OF SYSTEM ERROR DATA: CONSTANT BANDWIDTH MULTIPLEX; TEST CHANNEL ONLY

Data Frequency	$0.3 f_m$				$0.5 f_m$				$1.0 f_m$			
	Phase Null Only		Phase and Amp Null		Phase Null Only		Phase and Amp Null		Phase Null Only		Phase and Amp Null	
Channel (kc)	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW
No. 6 56 kc ±2 kc	0.42	3.0	0.42	3.0	1.3	6.0	1.2	5.4	2.4	8.5	0.30	2.2
No. 10 88 kc ±2 kc	0.39	2.5	0.39	2.5	1.5	6.8	1.1	4.5	1.9	7.0	0.27	2.0
No. 14 120 kc ±2 kc	0.54	3.2	0.54	3.2	1.8	7.4	1.6	7.0	2.4	8.0	0.31	2.2
No. 19 160 kc ±2 kc	0.60	3.8	0.60	3.8	2.0	8.0	1.8	8.0	1.9	7.0	0.30	2.0

TABLE I-3.6-8
SUMMARY OF SYSTEM ERROR DATA: COMBINATIONAL BANDWIDTH MULTIPLEX

Data Frequency	0.3 f_m				0.5 f_m				1.0 f_m			
	Phase Null Only		Phase and Amp Null		Phase Null Only		Phase and Amp Null		Phase Null Only		Phase and Amp Null	
Channel (kc)	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW
No. 8 3.0 kc ±7.5%	0.16	0.60	0.16	0.60	0.18	0.80	0.18	0.80	1.4	4.5	0.12	0.50
No. 6 56 kc ±2 kc	1.2	6.5	1.2	6.5	1.7	8.0	1.4	7.0	2.7	11.0	0.55	3.0
No. 10 88 kc ±2 kc	0.85	4.0	0.85	4.0	1.5	8.0	1.2	5.0	2.0	8.5	0.42	2.0
No. 14 120 kc ±2 kc	1.5	6.5	1.5	6.5	1.9	8.0	1.6	7.0	2.6	10.0	0.44	2.5
No. 19 160 kc ±2 kc	1.6	7.0	1.6	7.0	2.2	9.0	1.9	8.0	2.4	9.5	0.51	3.0

TABLE I-3.6-9
SUMMARY OF SYSTEM ERROR DATA: COMBINATIONAL BANDWIDTH MULTIPLEX; TEST CHANNEL ONLY

Data Frequency	0.3 f_m				0.5 f_m				1.0 f_m			
	Phase Null Only		Phase and Amp Null		Phase Null Only		Phase and Amp Null		Phase Null Only		Phase and Amp Null	
Channel (kc)	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW	rms % FBW	p-p % FBW
No. 8 3.0 kc ±7.5%	0.15	0.60	0.15	0.60	0.18	0.80	0.18	0.80	1.4	4.0	0.11	0.60
No. 6 56 kc ±2 kc	1.1	4.5	1.1	4.5	1.4	5.5	1.1	4.6	2.4	8.0	0.25	1.4
No. 10 88 kc ±2 kc	0.74	3.0	0.74	3.0	1.4	6.0	1.1	3.5	1.8	6.0	0.20	1.0
No. 14 120 kc ±2 kc	1.4	5.5	1.4	5.5	1.9	7.0	1.6	5.5	2.7	9.5	0.25	1.0
No. 19 160 kc ±2 kc	1.5	6.0	1.5	6.0	2.0	7.0	1.9	7.0	2.0	7.0	0.27	1.0

3.7 TAPE-RECORDER ERRORS

For each of the basebands evaluated, a tape recorder was included in the experimental system (Figures I-3.1-1 and I-3.1-3), and the tape-speed-compensation improvement as well as the increase in system output noise was determined.

3.7.1 Proportional-Bandwidth Basebands

Figure I-3.1-1 in section 3.1 shows the inclusion of the tape recorder in the laboratory system. A 250-kc reference tone was added to the de-emphasized receiver output and the composite signal was recorded at a level of 1 volt rms. On playback, the subcarrier discriminator output noise on representative channels was measured and compared to the output noise with the tape recorder bypassed. In each case, the difference in output noise was measured with the channel unmodulated at center frequency and at bandedge, with and without tape-speed compensation. The other channels in the multiplex were deviated full bandwidth at their maximum rate. An attempt was made to check the tape-recorder performance with the test channel modulated using a null technique to determine system error between input and output; however, time-base jitter prevented a satisfactory null and the technique was abandoned. Figure I-3.7-1 shows a summary of the data for the IRIG baseband, and Figure I-3.7-2 shows a summary of the data for the expanded baseband.

In each case, inclusion of the tape recorder was found to increase the average system noise by approximately 5 db for each of the basebands. Since a tape-speed-compensated, high-quality recorder was used, the amount of wow-and-flutter found was comparatively small. Figure I-3.7-3 shows a photograph of typical discriminator outputs when the tape recorder is used. The improvement due to tape-speed compensation was found to be 10 to 12 db in the low-frequency channels and as little as 3 db in the high-frequency channels. The effect of the tape recorder was also determined for the IRIG baseband multiplex operating at deviation ratios of 1 and 2, in which case the normal output noise was much greater than the noise caused by the tape recorder.

3.7.2 Constant- and Combinational-Bandwidth Basebands

Figure I-3.1-3 in section 3.1 shows the inclusion of the tape recorder in the laboratory system. The tape recorder used for the constant- and combinational-bandwidth evaluation was a slightly modified Ampex FR 1400; the borrowed Mincom machine used in the proportional-bandwidth evaluation, as well as the first Ampex FR 1400, had to be returned prior to the tape-recorder test. The characteristics of the machine used in the system evaluation are contained in section 2.9.

In the constant- and combinational-bandwidth system, the receiver output was normally de-emphasized. The 240-kc reference tone was added for tape-speed compensation and for synthesis of the frequencies needed for detranslator operation. The composite signal was thus either recorded or applied directly to the remainder of the system. The record level used was 0.5 volt rms, which provided a normal operating level of 1.4 volts peak. In an attempt to determine the effect of record level, data was taken on constant-bandwidth channel 6 output noise as a function of record level and is shown in Figure I-3.7-4. Although the 0.5 volt rms level was optimum with no rf link, there was little difference between record levels of 0.4 to 1.0 volt rms with the complete system.

Figure I-3.7-5 summarizes the data for the increase in channel output noise with the use of the tape recorder for both the constant- and combinational-bandwidth basebands. Again, there was little improvement with tape-speed compensation, since so little wow and flutter was present. The increase in output noise due to the tape recorder was less than 3 db for the constant-bandwidth channels but increased to approximately 6 db for the IRIG channels.

In addition to the increase in channel output noise due to the tape recorder, the intermodulation test was repeated with the tape recorder included in the system. Figure I-3.7-6 is a summary of this data and shows little increase in intermodulation due to the inclusion of the tape recorder; however, with no rf link present, it can be seen that the tape recorder increases the intermodulation slightly.

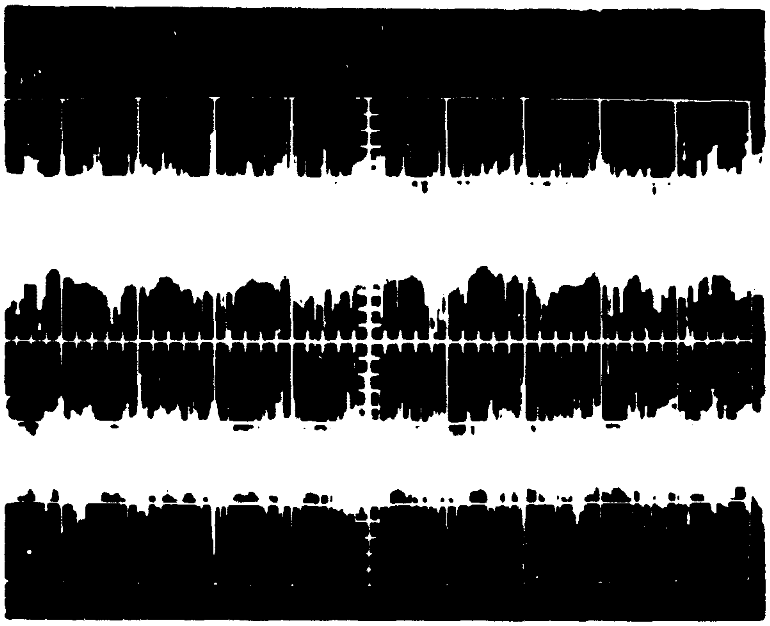
The detailed procedure for the tape-recorder test as well as the measured data and intermodulation photographs are included in section 3.6 of Volume II.

TABLE I-3.7-1
SUMMARY OF TAPE RECORDER DATA FOR IRIG PROPORTIONAL BANDWIDTH MULTIPLEX

		Increase In System Output Noise			
		No TSC		TSC	
System Description	Channel (kc)	CF (db)	LBE (db)	CF (db)	LBE (db)
Standard IRIG 18 Channel PBW Multiplex	3.0±7.5%	7.1	9.2	1.6	3.3
	70.0±7.5%	10.8	11.3	7.3	7.3
18 Channel PBW Multiplex DR = 1	0.96±7.5%	1.1	0.0	1.1	0.0
	3.0±7.5%	1.4	0.5	1.4	0.5
	7.35±7.5%	3.8	3.2	3.8	3.2
	22.0±7.5%	5.6	6.8	5.6	6.8
	70.0±7.5%	5.6	4.4	5.3	3.5
18 Channel PBW Multiplex DR = 2	0.96±7.5%	2.8	0.3	2.8	0.3
	3.0±7.5%	4.3	1.2	2.8	0.7
	7.35±7.5%	5.1	4.9	4.1	4.1
	22.0±7.5%	5.4	6.8	5.4	6.8
	70.0±7.5%	7.7	7.2	6.6	9.5
IRIG Channels 1 thru 16 and E PBW Multiplex	3.0±7.5%	14.0	6.6	2.9	3.1
	70.0±15%	10.8	9.3	8.3	7.4

TABLE I-3.7-2
SUMMARY OF TAPE RECORDER DATA FOR EXPANDED PROPORTIONAL BANDWIDTH MULTIPLEX

		Increase In System Output Noise			
		No TSC		TSC	
System Description	Channel (kc)	CF (db)	LBE (db)	CF (db)	LBE (db)
21 Channel Proportional Bandwidth Multiplex	3.0±7.5%	13.7	8.3	3.1	1.8
	70.0±7.5%	7.5	7.1	2.5	2.7
	93.0±7.5%	9.7	7.9	4.0	2.9
	124.0±7.5%	6.6	10.1	2.5	3.2
	165.0±7.5%	10.9	11.1	6.5	6.5
Channels 1 Thru 19 and H Proportional Bandwidth Multiplex	3.0±7.5%	14.4	10.7	4.2	2.7
	70.0±7.5%	8.7	7.6	2.7	2.3
	93.0±7.5%	7.1	8.0	2.1	2.4
	165.0±15%	7.6	6.5	5.6	3.7



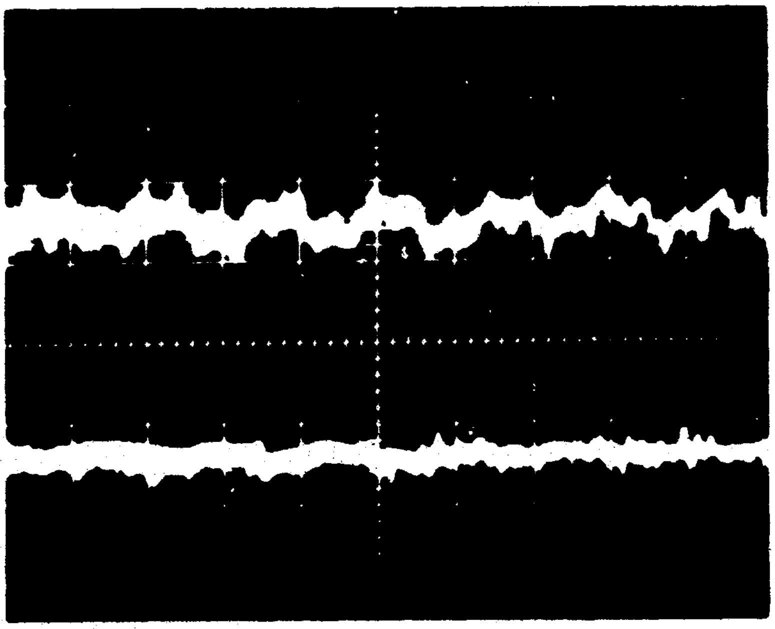
Top: Without TSC

Bottom: With TSC

Vertical: 0.1V/cm
(1% FBW/cm)

Horizontal: 0.1 ms/cm

a. 70 kc ±7.5% Channel - DR = 5



Top: Without TSC

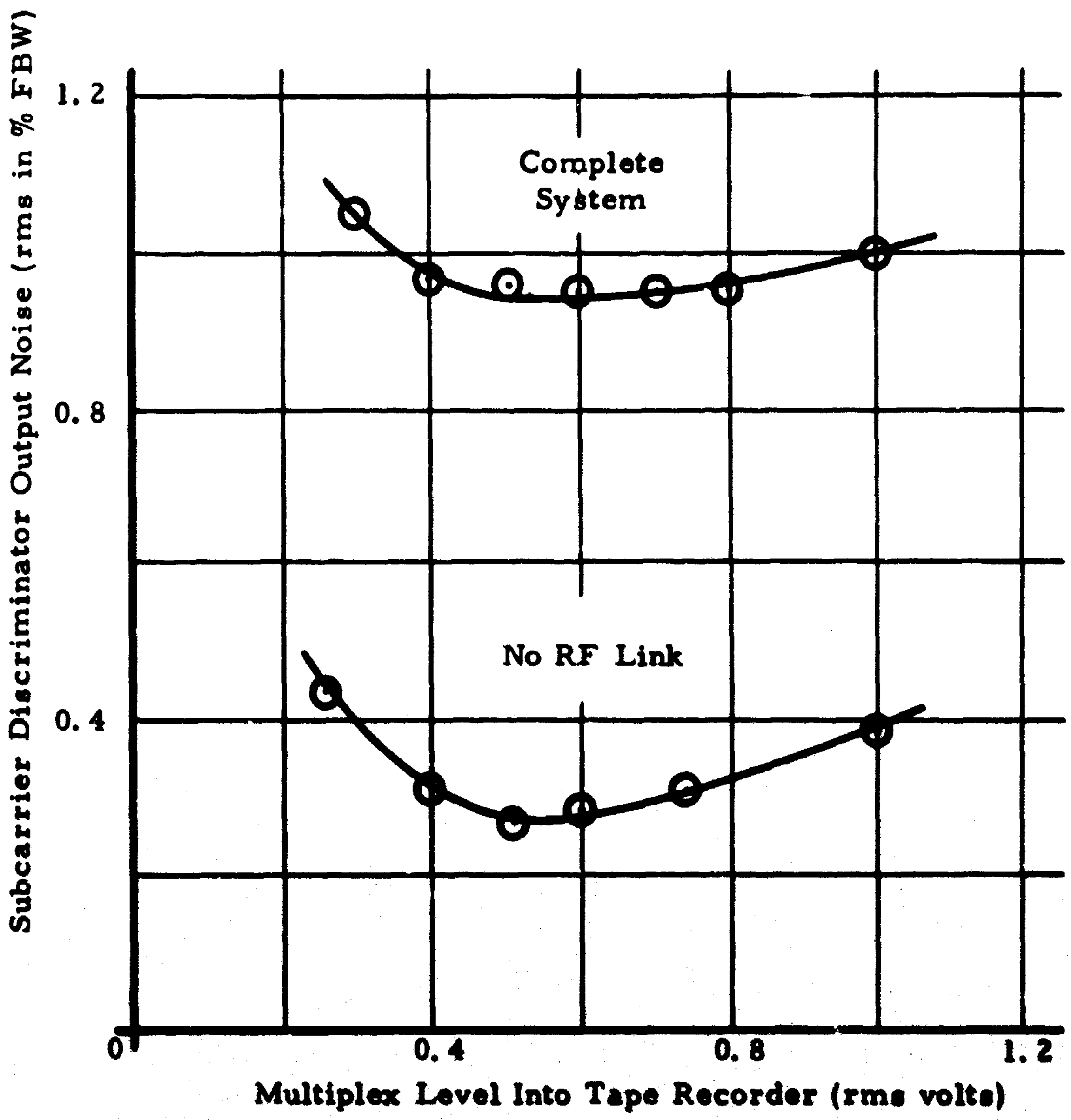
Bottom: With TSC

Vertical: 0.1V/cm
(1% FBW/cm)

Horizontal: 0.1 ms/cm

b. 3.0 kc ±7.5% Channel - DR = 5

FIGURE I-3.7-3
TAPE RECORDER WOW AND FLUTTER AT SUBCARRIER DISCRIMINATOR OUTPUT FOR IRIG MULTIPLEX



Conditions:
Channel 6: DR = 2 and at 1/2 high bandedge
All Other Channels: FBW modulation at f_m
Tape Speed Compensation: On

FIGURE I-3.7-4
CHANNEL 6 OUTPUT NOISE AS A FUNCTION OF
CONSTANT BANDWIDTH MULTIPLEX LEVEL INTO TAPE RECORDER

TABLE I-3.7-5
SUMMARY OF TAPE RECORDER DATA FOR CONSTANT AND COMBINATIONAL BANDWIDTH MULTIPLEXES

			Increase In System Output Noise Due To Inclusion Of Tape Recorder			
System Description	Channel		No TSC		TSC	
	No.	Frequency (kc)	CF (db)	BE (db)	CF (db)	BE (db)
Constant Bandwidth Multiplex	6	56 ±2	1.7	2.3	0.9	1.2
	10	88 ±2	2.0	1.5	0.8	1.1
	14	120 ±2	2.0	1.9	1.3	1.3
	19	160 ±2	2.1	3.0	1.6	2.5
Combinational Bandwidth Multiplex	8	3.0 ±7.5%	5.6	2.6	2.1	0.8
	6	56 ±2	2.6	2.9	1.5	2.6
	10	88 ±2	3.0	2.1	1.1	1.4
	14	120 ±2	2.2	1.9	1.4	1.5
	19	160 ±2	2.2	2.1	2.1	1.9

TABLE I-3. 7-6
SUMMARY OF TAPE RECORDER INTERMODULATION DATA: CONSTANT AND COMBINATIONAL BANDWIDTH MULTIPLEXES

Test Conditions:
Constant Bandwidth: MI = 2, DR = 2
Proportional Bandwidth: MI = 5, DR = 5

			Without Tape Recorder		With Tape Recorder	
System Description	Channel		Peak-Peak % FBW	Max. rms % FBW	Peak-Peak % FBW	Max. rms % FBW
	No.	Freq. (kc)				
Constant Bandwidth Multiplex	6	56 ±2	5.5	0.76	5.0	0.67
	10	88 ±2	3.5	0.46	3.8	0.45
	14	120 ±2	3.2	0.46	3.2	0.49
	19	160 ±2	3.7	0.47	4.0	0.53
Combinational Bandwidth Multiplex	8	3.0 ±7.5%	0.35*	0.04*	0.5	0.07
	6	56 ±2	6.0 *	0.88*	6.2	1.02
	10	88 ±2	4.5 *	0.50*	3.8	0.56
	14	120 ±2	3.5 *	0.51*	4.0	0.59
	19	160 ±2	5.0 *	0.58*	5.0	0.68
** No RF Link	** 6	56 ±2	1.5	0.24	2.2	0.36

*Modulation was 0.1 f_m

3.8 PULSE MODULATION

To determine the system performance for pulse-type transmission, each of the proportional-bandwidth basebands containing a wideband (±15%) channel in the highest frequency position was evaluated using PAM, PDM, and PCM signals. The IRIG baseband channel at 70 kc ±15% was modulated with 900 samples per second for PAM and PDM, and 21,000 bits per second for PCM. The expanded baseband channel at 165 kc ±15% was modulated with 2100 samples per second for PAM and PDM, and 49,500 bits per second for PCM.

In the PAM case (Figure I-3.8-1), the test determined how accurately the individual pulses reached their full scale value for 40%, 50%, and 70% duty cycles. For both basebands, the amplitude errors were less than 1% of full scale. Photographs of the channel response to PAM, as well as the detailed test procedures, are shown in section 3.7 of Volume II.

For PDM (Figure I-3.8-1), the test determined the change in pulse durations through the system. Errors of less than 0.5% of full scale were measured for both basebands. Photographs of the input and output PDM and the detailed test procedures are shown in section 3.7 of Volume II. The effect of pulse modulation on crosstalk in the adjacent channel was measured; no significant difference between basebands were found. The increase in adjacent channel crosstalk due to zero-scale PDM was found to be less than 0.4% of full bandwidth for ±7.5% deviation, and less than 0.9% of full bandwidth for ±15% deviation. Photographs of the channel outputs are shown in section 3.7 of Volume II for the adjacent channel crosstalk test.

For the PCM test (Figure I-3.8-2), the wideband channels were modulated 0.7 FBW at 21,000 bits per second for the IRIG baseband and 49,500 bits per second for the expanded baseband. The bit-error probability as a function of carrier-to-noise ratio was determined and is shown in Figure I-3.8-3. In addition, the effect of the PCM on the adjacent-channel crosstalk was measured and found to be negligible for the IRIG baseband; however, for the expanded baseband, the output noise of the adjacent channel increases from 1% to 1.5% of full bandwidth. The detailed procedure for the PCM test, the bit-error-probability data, and the photographs of the adjacent-channel crosstalk are shown in section 3.7 of Volume II.

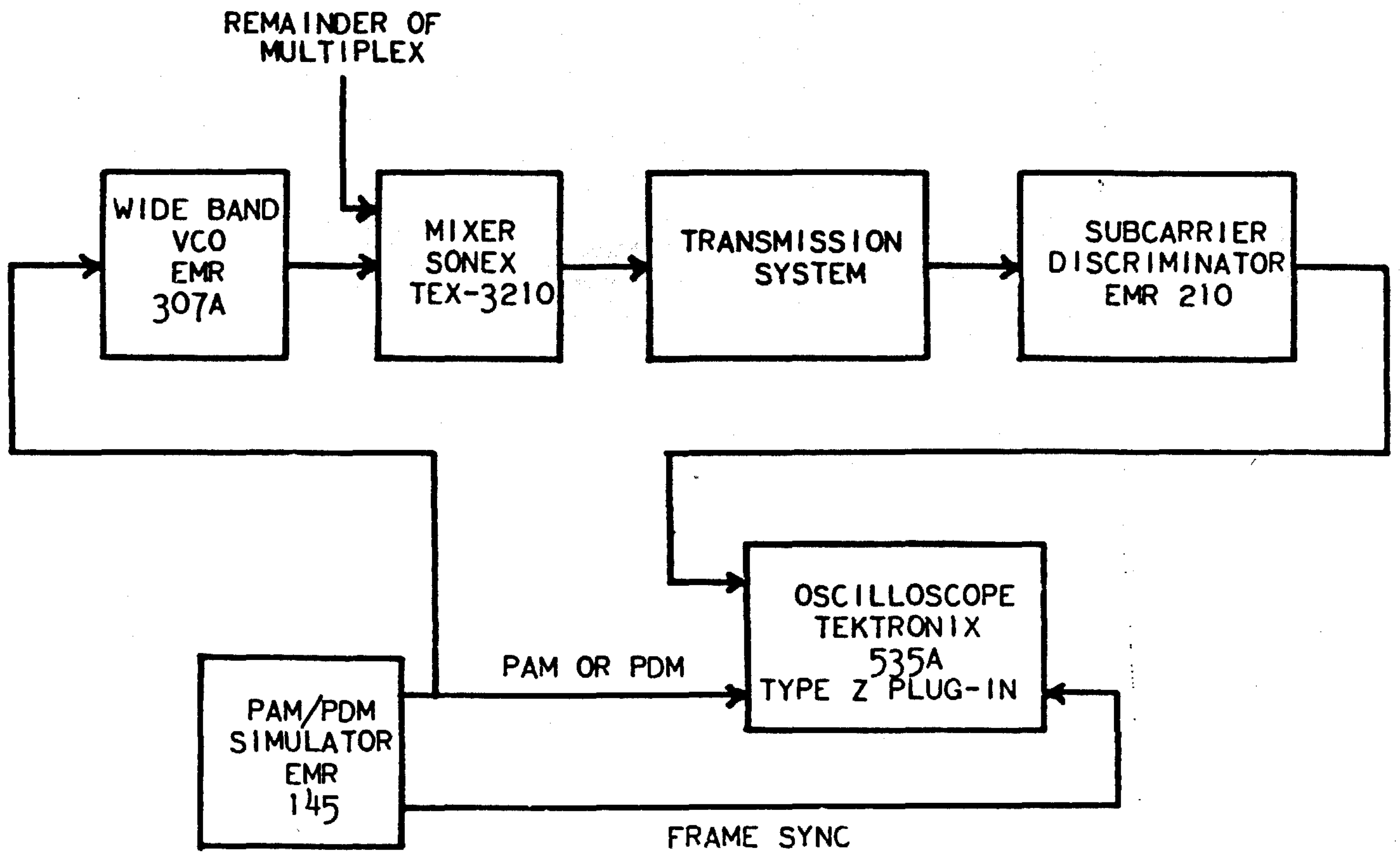


FIGURE I-3.8-1
PAM/PDM BLOCK DIAGRAM

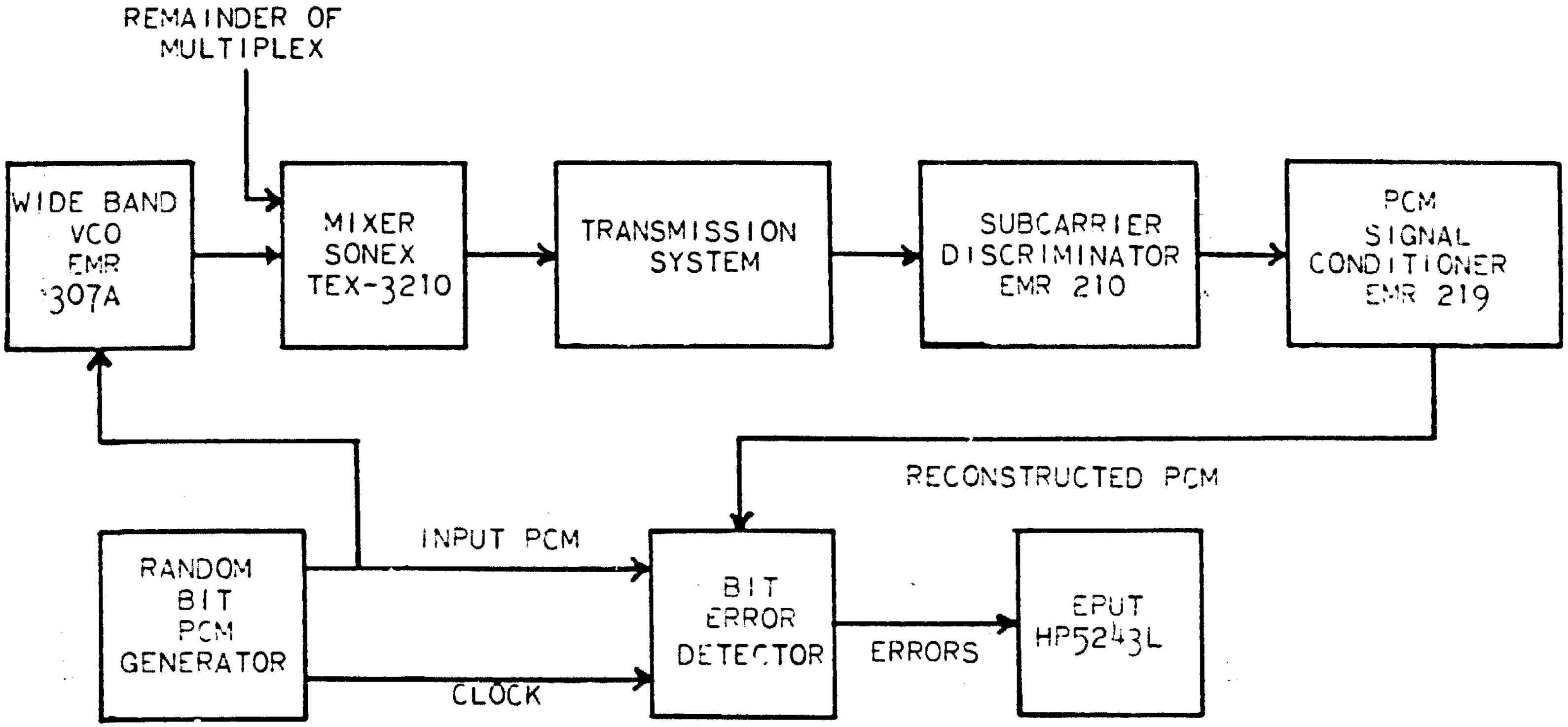


FIGURE I-3.8-2
PCM BLOCK DIAGRAM

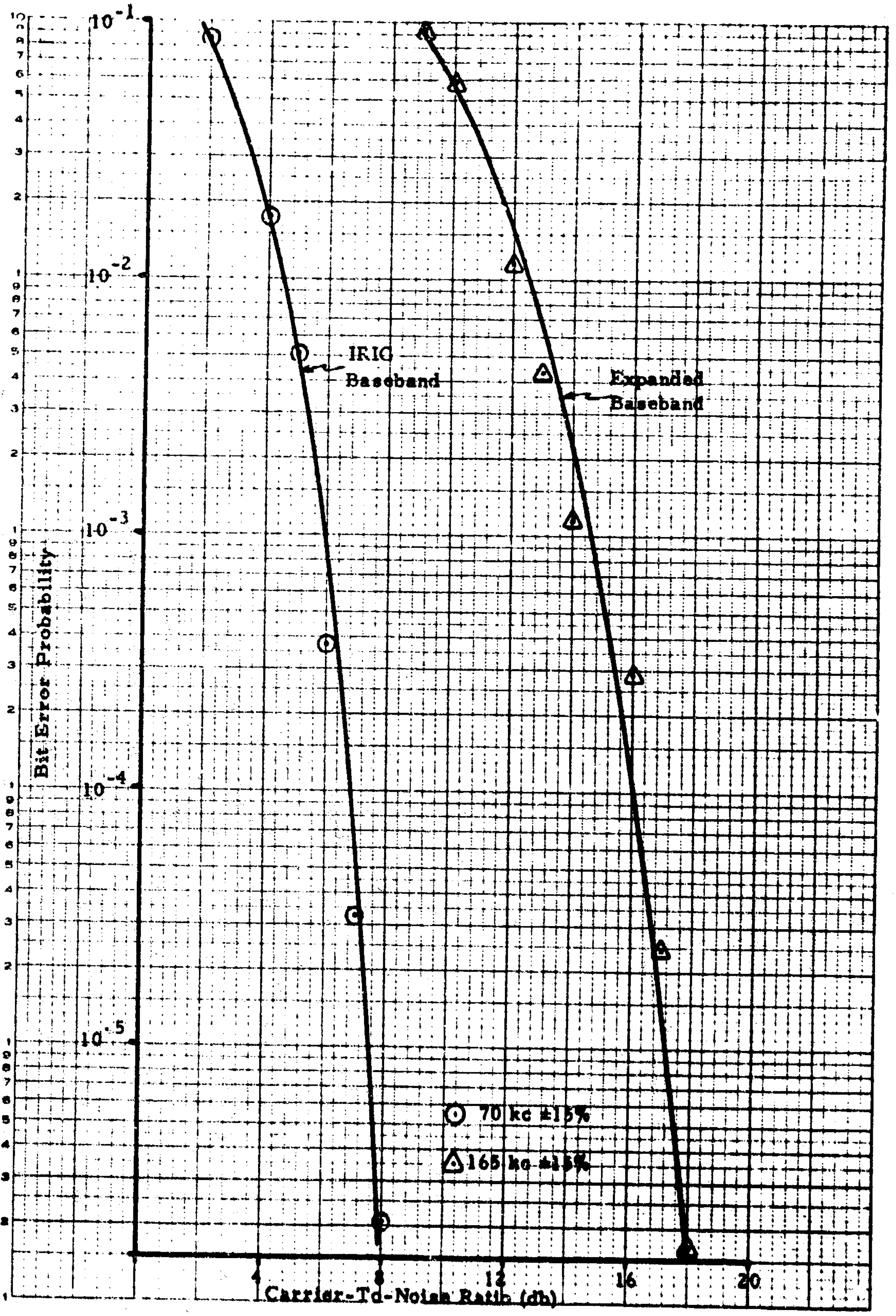


FIGURE I-3.8-3
PCM BIT ERROR PROBABILITY VS
CARRIER-TO-NOISE RATIO
PROPORTIONAL BANDWIDTH MULTIPLEXES

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 DISCUSSION OF RESULTS

The results of the equipment evaluation show that the majority of the equipment selected for evaluation is adequate for use with expanded FM/FM basebands. With the possible exception of the transmitter, none of the airborne equipment showed signs of inadequate performance. The EMR Model 121 Transmitter modulator has insufficient bandwidth, which resulted in increased distortion at frequencies higher than standard IRIG channels. The deviation gain or sensitivity of the Leach Model FM 200, which was used in the laboratory telemeter, began to deteriorate at the higher frequencies; however, the distortion was still linearily related to the deviation and modulating frequency. For even-higher subcarrier frequencies, the deviation sensitivity rolloff would become a problem as would the increase in distortion. The additional airborne equipment needed for the constant-bandwidth system presents no particular problem since the equipment was specifically designed for this type of application. No problems were encountered during the ground equipment evaluation; however, intermodulation caused by the receiver IF was evident during the system test. The subcarrier discriminator, tape recorder, and ground translation equipment offer no problem to expansion of the baseband. With the exception of the transmitter and receiver, expansion to subcarrier channel frequencies of 300 kc seems reasonable.

The results of the system test will be considered test by test and the conclusions from the total program considered in the next paragraph. The experimental pre-emphasis optimization pointed out the nontriangular shape of the receiver noise and lack of the theoretically expected 3/2 power taper. From the signal-to-noise test results at a carrier-to-noise ratio of 9 db, the discriminator output signal-to-noise ratios were found to be reasonably constant from channel to channel. Therefore, the use of the subcarrier-to-noise ratio as the parameter for optimization, instead of the discriminator output signal-to-noise ratio, is equivalent. For carrier-to-noise ratios other than 9 db, the character of the receiver noise changes; therefore, the pre-emphasis is no longer optimized. Optimizing a pre-emphasis schedule is a time-consuming task at best, but the use of measurements of subcarrier-to-noise ratio does simplify the task somewhat.

The radiated-spectrum test presented the major problem in the system tests because of the difficulty in applying the initial radiated-spectrum specification:

> The 40-db bandwidth of the modulated carrier, referenced to the unmodulated carrier, shall not exceed ±320 kc. Carrier components appearing outside a ±500-kc bandwidth shall not exceed −25 dbm.

This specification is applicable to line or discrete spectra where the magnitude of lines outside the ±320-kc bandwidth is readily apparent; however, for continuous spectra this bandwidth is not apparent. For continuous spectra a density or magnitude in a particular measurement bandwidth is required. Since both discrete and continuous spectra are present with extended baseband (e.g., continuous for the 18-channel IRIG baseband and discrete for the 21-channel constant-bandwidth baseband), the problem is thus one of defining a specification that is applicable to both spectra.

During the proportional-bandwidth-baseband evaluation the radiated spectrum specification evolved to:

> The power spectral density, as measured in a 1000-cps bandwidth, outside a bandwidth of ±320 kc shall not exceed −50.5 db referenced to the unmodulated carrier. Carrier components outside ±500-kc bandwidth shall not exceed −25 dbm.

The application of this specification to the 18-channel IRIG multiplex placed 99.93% of the transmitter energy in the assigned bandwidth of ±320 kc. For the remaining basebands which presented spectra which were either discrete, continuous, or combinations of both, the same specification was used. The extent to which the transmitter energy is thus constrained is not known; however, the application of the individual specification to all basebands provided a means for comparison of system test data.

The intermodulation tests emphasize the fact that the intermodulation products falling into a particular channel are intimately related to the position or deviation of all the other subcarrier channels in the multiplex. To reduce the infinite number of possible measurements, the intermodulation test was designed to produce a reasonable worst-case condition. This condition was simulated by slowly deviating all channels independently from bandedge-to-bandedge while sweeping the test or search channel at a much slower rate. This procedure gives a reasonable probability of observing worst-case peak-intermodulation products on the photographs of the search-channel output.

Systematic tests indicated that the cause of the intermodulation products was the receiver IF. Any nonlinearity in the receiver IF causes receiver output harmonic distortion, which for a subcarrier multiplex appears as intermodulation. The intermodulation products of the higher-frequency large-amplitude subcarriers fall into the passband of the smaller-amplitude low-frequency channels, causing beat notes which appear in the subcarrier discriminator output. This problem can be reduced by reducing the nonlinearity in the receiver IF--by providing less variation in envelope delay and/or less amplitude variation through the IF filter. One way to impelement this improvement is to use a wider IF, but this causes the receiver to threshold at a higher carrier-to-noise ratio. A trade-off study between these two factors was beyond the scope of this study.

The problem of small nonlinearities in the transmission equipment must be considered when expansion to larger IF bandwidths is considered, especially if a greater number of subcarriers is used. The required pre-emphasis causes a large variation between the amplitudes of the high- and low-frequency channels. Thus, any small nonlinearity can cause intermodulation products due to the high-frequency channels which could completely overwhelm the small-amplitude low-frequency channels. Increasing the transmitter deviation and correspondingly increasing the radiated-spectrum limit does not solve this problem, since the problem is created by the relative amplitudes of the high- and low-frequency channels. Thus, any larger expansion of the number of channels in a multiplex will require exacting linearity standards on all equipment used.

The signal-to-noise tests are particularly interesting because the test measures performance through two FM demodulation processes, in the receiver and in the subcarrier discriminator. The results are reasonable when compared to the calculated performance. As an example, consider the 70 kc ±7.5% channel in the IRIG 18-channel system at a carrier-to-noise ratio of 14 db:

> The relation between carrier-to-noise ratio and discriminator output signal-to-noise ratio for an FM/FM system above threshold given by K. M. Uglow(1) is:
>
> $$(S/N)_d = (S/N)_c \left[3/4\right]^{1/2} \left[\frac{B_c}{F_{ud}}\right]^{1/2} \frac{f_{dc}}{f_s} \frac{f_{ds}}{F_{ud}}$$
>
> $(S/N)_d$ = the discriminator output signal-to-noise ratio
>
> $(S/N)_c$ = the carrier-to-noise ratio at the IF (14 db or 5 for the example)
>
> B_c = the IF bandwidth (500 kc)
>
> F_{ud} = cutoff frequency of discriminator output filter (1470 cps. Note: this number is 1.4 times the nominal channel data-cutoff frequency of 1050 cps; see Figure I-2.8-3)
>
> f_s = subcarrier center frequency (70 kc)
>
> f_{dc} = carrier peak deviation due to particular subcarrier (63.6 kc)
>
> f_{ds} = subcarrier peak deviation (5250 cps)
>
> $$(S/N)_d = (5) \left[3/4\right]^{1/2} \left[\frac{5000,000}{1470}\right] \left(\frac{63,600}{70,000}\right) \left(\frac{5250}{1470}\right)$$
>
> $(S/N)_d$ = 258 or 48 db.

---

(1)K. M. Uglow, "Noise and Bandwidth in FM/FM Radio Telemetry," IRE Transactions on Telemetry and Remote Control, May 1957, pp. 19-22.

From Table I-3.5-2, the measured value of discriminator output signal-to-noise ratio was 45.4 db. There are several assumptions which account for the 2.6-db error; however, the primary one is the assumption of ideal (square-sided) filters for the IF, BPIF, and LPOF. For example, with sine-wave modulation, the subcarrier signal is attenuated 1 db on an average rms basis by the rolloff of the BPIF, and the noise is increased approximately 1 db because the equivalent noise bandwidth of the BPIF is a factor of 1.1 greater than the 3-db bandwidth. Thus, the measurements are considered reasonably valid. Other similar calculations can be made on other channels or the individual FM signal-to-noise performance can be verified from the data in section 3.5.

It should be pointed out that the signal-to-noise performance for the constant-bandwidth channels operating at a deviation ratio of 2 seems poor when compared to the IRIG channels with a deviation ratio of 5. This performance is due to two facts: (1) the rf modulation index per subcarrier is very low; for example, channel 17 (144 kc ±2 kc) operates at a modulation index of only 0.076, and (2) that the subcarrier channel is operated at a modulation index of 2.

This decrease in allowable transmitter deviation with the constant-bandwidth baseband causes the signal-to-noise performance to be degraded. Since the performance above threshold is dependent upon the subcarrier deviation ratio, a more straightforward comparison of the basebands can be made by considering the subcarrier-to-noise ratio at receiver threshold shown in Table I-4.1-1. Also included in Table I-4.1-1 is the total data bandwidth of each baseband, for operation at a deviation ratio of 2 on constant-bandwidth channels and a deviation ratio of 5 on proportional-bandwidth channels.

Assuming subcarrier threshold at a 9-db subcarrier-to-noise ratio, and using the criterion of adequate design causing the receiver and subcarrier to threshold at the same carrier-to-noise ratio, the 21-channel constant-bandwidth baseband signal-to-noise performance is marginal. If the number of channels in the constant-bandwidth baseband is reduced to 16 (i.e., group D is removed), and the transmitter deviation increased appropriately, the subcarrier-to-noise ratio increases 6 db. The trade-off of 6-db signal-to-noise performance for five channels appeared justified, and the 21-channel constant-bandwidth baseband was used throughout the system evaluation.

The system error data shows that the major data distortion is caused by filter attenuation in the subcarrier discriminator. This effect is especially true at reduced deviation ratios. The system errors due to intermodulation and harmonic distortion are usually masked by the error due to filter attenuation. If amplitude corrections are made, the system errors are reduced significantly and the small amounts of harmonic distortion are visible, especially at the 0.5 f_m position in the data passband. In all cases, the system errors that do occur are not increased by the expansion of the baseband.

The results of the tape-recorder test show that an increase in system output noise occurs with the addition of the tape recorder, but like the system error data, the results do not change significantly with the expansion of the baseband. The results of the test on the proportional-bandwidth basebands show a greater effect due to addition of the tape recorder than do the constant- or combinational-bandwidth basebands. Although the tests were performed on different machines, the major difference may lie in the level that was used for recording. The manufacturers' specified normal record level is a 1-volt rms sine wave, which causes the input-level meter to deviate to 0 db. The proportional-bandwidth multiplex was recorded at 0 db as read on the input-level meter. Since the multiplex closely approximates normal or gaussian noise, the peak level of the input signal was ±3 volts, (i.e., the 3σ point). This peak record level is thus more than two times the normal record level of ±1.4 volts for a sine-wave input. This difference in peak levels was not noticed until after the proportional-bandwidth multiplex had been evaluated and the Mincom G107 returned to the manufacturer. For the constant-bandwidth evaluation, an Ampex FR 1400 was used with a multiplex record level of 0.5 volt rms. The data of Figure I-3.7-4 shows that the increase in output noise due to variations of record levels between 0.5 and 1.0 volt rms was less than 0.6 db. It was thus concluded that the difference in record level used for the proportional- and constant-bandwidth baseband evaluation had little effect on the resulting data.

The pulse modulation data for PAM or PDM shows no decrease in accuracy or significant increase in adjacent channel noise with the expansion of the proportional-bandwidth baseband. The PCM bit-error probability data for the expanded baseband shown in Figure I-3.8-3 is degraded 8.5 to 9 db relative to the performance of the IRIG baseband. This difference is due to the maximum allowable transmitter deviations of each baseband. The 70 kc ±15% channel of the IRIG baseband has a 90-kc peak-transmitter deviation, whereas the 165 kc ±15% channel has only 62.5 kc peak. Assuming triangular receiver output noise and operation above threshold, this difference should result in 14 db difference in discriminator output signal-to-noise performance or bit-error probability; however, neither of the assumptions are completely valid and the degradation is less (i.e., the receiver output noise is not completely triangular, and the receiver is operating below threshold in the area of interest for the IRIG baseband).

With the abundance of measured data, there are numerous areas of general FM/-FM system performance which could be analyzed, plotted, discussed, and traded-off; however, the primary effort has been to determine and discuss those factors which affect expansion of the baseband.

TABLE I-4. 1-1
BASEBAND COMPARISON OF TOTAL DATA BANDWIDTH AND SIGNAL-TO-NOISE PERFORMANCE AT RECEIVER THRESHOLD

Baseband	DR	$(S/N)_s$ at Receiver Threshold	Total Data Bandwidth
18-Channel IRIG	5	23 db	4,009 cps
21-Channel Expanded Proportional Bandwidth	5	10 db	9,739 cps
21-Channel Constant Bandwidth	2	5.5 db	21,000 cps
16-Channel Constant Bandwidth	2	11.5 db	16,000 cps
32-Channel Combinational Bandwidth	1 & 2	8.5 db	21,415 cps

4.2 CONCLUSIONS

The results of this program have demonstrated the feasibility of expanding the FM/FM structure described in IRIG Document No. 106-60, June 1962 revision, to include a larger number of channels, choice of constant- or proportional-bandwidth subcarrier channels and greater flexibility in operating parameters.

Experimental evaluation of the laboratory telemeter has demonstrated the feasibility of adding three proportional-bandwidth (±7.5% or ±15%) channels to the standard IRIG baseband at center frequencies of 93 kc, 124 kc, and 165 kc. With the exception of signal-to-noise performance, no significant degradation of system accuracy was found when the expanded baseband was used. Although the expanded baseband signal-to-noise performance is reduced 12 db compared with that of the standard IRIG baseband, the reduced performance should not be considered a penalty; rather, the superior performance of the standard IRIG baseband should be considered a luxury. A conservative design criterion requires transmitter deviation sufficient only to cause the receiver and the subcarrier discriminators to threshold at the same carrier-to-noise ratio. The system parameters used in the evaluation are generous for the standard IRIG baseband, and allow the subcarrier discriminators to threshold at a carrier-to-noise ratio 5 db below the receiver threshold level, whereas the system operating with the expanded baseband provides receiver and subcarrier threshold at the same carrier-to-noise ratio.

The performance of the standard IRIG baseband was evaluated for operation at deviation ratios of 1 and 2 in an attempt to add versatility to the operation of the standard baseband. The operation of the IRIG baseband with a deviation ratio of 1 suffers from extreme intermodulation noise; therefore, this mode of operation is not recommended. Operation with a deviation ratio of 2 is adequate for applications requiring accuracies no greater than 5% of full bandwidth. Operation at deviation ratios greater than 2 is thus recommended for those systems requiring greater bandwidth and less accuracy than the standard deviation ratio of 5.

The equipment evaluation portion of the program has shown that typical field equipment can be used successfully with an expanded proportional-bandwidth baseband. The exceptions found were in equipment that had been designed with an upper frequency limit of 70 kc; however, the more modern equipment presently available is capable of operating at the extended frequencies. The majority of field equipment was designed for proportional-bandwidth operation; thus, the equipment necessary for constant-bandwidth operation was necessarily new. For constant-bandwidth applications the VCO design is simply a deviation sensitivity change, and the subcarrier discriminators require only appropriate plug-ins; however, the translation equipment was designed expressly for constant-bandwidth applications. The rf equipment required no modification.

The construction and evaluation of the constant-bandwidth baseband has shown the feasibility of expanding the FM/FM baseband to include a constant-bandwidth baseband with the binary configuration. The system tests show no significant increase in errors with the constant-bandwidth baseband compared to the IRIG baseband operated at a deviation ratio of 2, with the exception of signal-to-noise performance at receiver threshold, which is marginal for the 21-channel baseband. Ultimately, the user must decide if he can afford the signal-to-noise cost for the additional channels. The binary configuration allows the user to make this decision and to design the appropriate baseband with the number of channels needed. The operation of the channels in the constant-bandwidth baseband at deviation ratios less than 2 is not recommended. Accuracies of 5% of FBW can be expected with operation at a deviation ratio of 2, or 2% of FBW for operation at a deviation ratio of 4. For operation of the baseband with higher data rates and/or deviation ratios, the number of channels can be reduced and the deviation of each channel increased (e.g., ±4 kc or ±8 kc for channel spacings of 16 kc and 32 kc respectively). The performance of the constant-bandwidth baseband will improve with fewer channels in the multiplex since the number of intermodulation products will be reduced. The versatility and performance of the constant-bandwidth baseband, constructed in the binary configuration, thus fulfills the objectives of the FM/FM baseband expansion.

Finally, the combination of IRIG and constant-bandwidth channels into the combinational bandwidth baseband has been shown to be feasible and, in fact, to enhance the performance of the constant-bandwidth channels. Again, depending upon the user requirements, the binary configuration for the constant-bandwidth channels offers the versatility of being able to construct a baseband with almost unlimited combinations of IRIG and constant-bandwidth channels.

4.3 RECOMMENDATIONS

1. Revision of the FM/FM structure described in IRIG Document No. 106-60, June 1962 revision to include:

    a. ±7.5% or ±15% proportional-bandwidth channels at center frequencies of 93 kc, 124 kc, and 165 kc.

    b. Operation of the proportional-bandwidth baseband at deviation ratios of two or greater.

    c. A binarily constructed constant-bandwidth baseband with typical channel center frequencies located at increments of 8 kc as shown in Table I-1.5-2 and operated with deviations and deviation ratios shown in Table I-1.5-3.

    d. Operation of a baseband consisting of combinations of proportional- and constant-bandwidth channels recommended in a. and c. above. One such configuration is the baseband evaluated with the first 11 IRIG channels plus the 21 constant-bandwidth channels.

2. Revision of IRIG Document No. 106-60, June 1962 revision to include:

    a. Tape speed reference tones that are binarily related (e.g., 120 kc, 160 kc, 200 kc, and 240 kc) for use with the binary constant-bandwidth base bands.

    b. A specification on transmitter radiated spectrum which is applicable to both discrete and continuous spectra. The specification used in this program may be adequate; however, further investigation beyond the scope of this program is recommended to develop a specification that constrains the transmitter energy to a specific bandwidth and which is independent of baseband configuration. Also, the specification should be simple to measure with available equipment.

3. Further study relating specifically to the characteristics of the receiver IF and its effect on intermodulation products at the subcarrier level.