FINAL REPORT
PROJECT NO. A-312

INVESTIGATION AND STUDY OF COMMUNICATION INTERFERENCE REDUCTION TECHNIQUES

By

B. L. BLANKS, W. R. FREE, H. L. MCKINLEY,
R. E. MEEK, R. R. PROPP AND S. L. ROBINETTE

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I. PREFACE

This report presents the results of work on Contract No. AF-30(602)-1638 entitled "Investigation and Study of Communication Interference Reduction Techniques," for the period 1 December 1956 to 31 January 1958.

The principal contract specifications that guided this program of investigation and study are outlined as follows:

a. A study of the most feasible technique for construction of a voltage controllable linear r-f attenuator for an automatic volume control of UHF receivers with special emphasis given to the exploration of ferrite materials for this application.

b. A study of the intermodulation performance of currently available UHF vacuum tubes for use as receiver r-f amplifiers and mixers and a determination of the optimum (fixed) bias for minimization of the third-, fifth- and seventh-order intermodulation products.

c. A study of currently available UHF tubes for use as a plate mixer (first detector) including input and output networks.

d. Application of the most promising results of the above techniques to a typical UHF communication receiver.

Additional subjects closely allied with the above specifications were investigated when they showed promise of producing useful results. These were principally the investigation of a mathematical technique to describe the intermodulation characteristics of vacuum tubes and the study of filter configurations with improved characteristics.

The contract was sponsored by the Rome Air Development Center, Griffiss Air Force Base, New York.

All work was performed at the facilities of the Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia.
II. ABSTRACT

Three interference reducing techniques were investigated and results of the application of these techniques on a R361A/GR receiver were observed. These techniques were (1) fixed bias operation of r-f amplifiers and mixers, (2) use of plate mixer, and (3) AVC action by linear UHF attenuation.

Third-, fifth- and seventh-order intermodulation rejection properties were obtained on several currently available VHF and UHF tubes used as r-f amplifiers and mixers. Fifth- and seventh-order intermodulation was found negligible compared to third-order. All but a few types showed a bias point within the Class A region where maximum third-order rejection could be obtained. Type 6386 demonstrated the effectiveness of a tube possessing a nearly square-law transfer characteristic in reduction of intermodulation.

An analytic technique was developed to mathematically investigate tube non-linearities and a program was devised to employ the IBM 650 magnetic-drum computer. Results of this technique showed the possibility of evaluating a coefficient as high as the fourth order in a Taylor's series representation of a tube transfer characteristic.

Plate mixers, when scaled to compare with conventional mixers, were found to yield no improvement in their interference rejection properties or conversion characteristics.

A ferrite continuously variable linear attenuator was developed to provide AVC action on input UHF signals. Control of attenuation is obtained by adjustment of a magnetic field in a coaxial transmission system where ferrite sleeves are placed around the center conductor. A minimum attenuation of 40 db and a minimum insertion loss of 1.5 db were obtained with a VSWR of 1.5.
A mechanical attenuator utilizing a 156C-2 cavity filter was incorporated in a servo system driven by the receiver AVC voltage. Variation in attenuation was obtained by controlling the size of the coupling port (control of circuit mutual coupling) between the two cavities involved. The range of attenuation was 2 to 30 db.

Three experimental model r-f amplifiers were constructed and their performance was compared with the performance of the R361A/GR receiver r-f amplifier alone. Improved input selectivity and use of selected tube types (operating at fixed bias) in the experimental amplifiers provided 20 to 40 db better third-order intermodulation rejection. Receiver noise figure was considerably degraded when two of the experimental amplifiers were substituted for the regular amplifier.

Application of the various techniques revealed that fixed bias operation of r-f amplifier tubes in the R361A/GR receiver provided about 20 db improvement in third-order intermodulation rejection. Improvement of rejection yielded by using the ferrite attenuator for AVC was about 6 db over that condition where regular AVC is used.
III. INTRODUCTION

The basis for this contract was established principally by the results of work in Phase II of Contract No. AF-30(602)-673 entitled "Study Program for Investigation to Aid in Reduction and Prevention of UHF Interference." Phase II of that program was the investigation of circuits in existing UHF receiver and transmitter equipments and was aimed toward the development of techniques which would effect reduction of interference normally experienced in multi-channel operation of these units.

A. Statement of Problem

The most serious types of interference encountered in receivers, when receivers and transmitters are operated in close geographical and spectrum proximity, are intermodulation and cross-modulation interference. Experimental tests and theoretical analysis showed intermodulation to be the more serious of the two interferences. Both intermodulation and cross-modulation interferences are primarily produced by nonlinear mixing of off-channel signals in the r-f amplifier tubes and in the first mixer.

Four possible solutions to the problem of receiver interferences of this type were proposed. These were

1. to linearize the vacuum tube transfer characteristic or otherwise compensate for its nonlinear effects,
2. to keep small the magnitude of all signals impressed on the nonlinearities,
3. to develop mixer circuits possessing a high ratio of conversion gain to intermodulation production, and
4. to provide sufficient preselection to prevent interfering adjacent channel signals from appearing at the first and succeeding nonlinearities (tubes).
Techniques aimed at realizing the four solutions were suggested and the feasibility of the techniques was established in the report cited. The purpose of the present project was to further develop and evaluate the techniques.

B. Method of Approach

Initially the studies and results of Phase II of the previously cited contract were reviewed to aid in accomplishing the work program specified in the current contract. This program was scheduled into two phases of effort, the operation of one being contingent upon the results of the other. The first phase was the study and evaluation of the individual interference reducing techniques. The second phase was the testing of the relative effectiveness of these techniques applied to a typical UHF receiver such as the R-361A/GR receiver.

Particular items specified for investigation by the current contract were:

1. The measurement and evaluation of the third-, fifth-, and seventh-order intermodulation characteristics of currently available UHF mixer and amplifier tubes, observing the functional variation of these characteristics with respect to bias; and evaluating the possibility of establishing an optimum fixed bias for greatest interference rejection.

2. The study of the most feasible technique of a voltage controllable linear r-f attenuator as an AVC element of UHF receivers; special emphasis to be given to ferrite materials for this application. Investigation on this item was to aim toward the development and construction of an experimental model to be evaluated in application to a typical receiver system.

3. The evaluation of the performance of currently available UHF tubes in a plate mixer configuration. This investigation was to be aimed toward the construction of an experimental UHF plate mixer utilizing the results of the initial evaluation.
4. The investigation of closely allied items that showed good promise of enhancing or providing better understanding of the interference rejection properties of any of the preceding techniques.

5. Contingent upon the results of the previous investigations, to apply these techniques to a typical UHF receiver such as the R-361A/GR to determine the effectiveness of their interference reducing properties.

In fulfillment of Item 1 in the above specifications, 14 commercially available VHF and UHF tube types were measured. Initial measurements were carried out at low (ultrasonic) frequencies. Measurement of characteristics at UHF were performed later on 8 of the 14 tubes. Mathematical techniques to provide additional information on the intermodulation characteristics of these tubes were developed and applied concurrent with the laboratory measurements.

The initial study on the UHF linear attenuator was devoted primarily to the investigation of ferrite materials. Fundamental theory, material specifications and physical circuit configurations were the principal problems encountered. Of the other attenuation techniques investigated one which was based on control of mutual circuit coupling appeared most practical. The ensuing development of these two techniques led to the construction of two experimental model attenuators capable of being controlled by an AVC voltage.

The characteristics of tubes employed as plate mixers were studied first at low frequencies to provide data that could be compared with or related to UHF measurements which were made later. The large amount of intermodulation rejection shown by this circuit was offset by a considerable amount of conversion loss. A preliminary investigation of conventional (grid) mixers appeared to give more fruitful results and some effort was diverted from plate mixer study to further investigations of other types of mixers. Intermodulation rejection
characteristics as well as conversion gain were observed in functional relationship with grid bias.

C. Application of Results

Development of actual amplifier and mixer circuits to utilize the results of the investigation of intermodulation characteristics of amplifier and mixer tubes provided an opportunity to employ improved selective networks at the r-f amplifier input and at the output of the first mixer.

Applications of the various interference reducing techniques were tested on a R-361A/GR receiver. Experimental models of UHF amplifiers and mixers were constructed as adapters utilizing tube types showing good rejection characteristics. Provisions were made for adjusting bias to prescribed points to give maximum intermodulation rejection. Experiments were also made with inclusion of improved selective UHF input networks and a high frequency, highly selective crystal filter following the first mixer.

Observations were made on the improvement in intermodulation rejection and effect on receiver sensitivity and noise figure.

D. Conferences and Symposiums

Four contract technical conferences were held during the course of the contract period between technical representatives of RADC and technical representatives of Georgia Tech. The locations and dates of these conferences were

Rome Air Development Center - February 21, July 23-24, 1957, and
Georgia Institute of Technology - April 11-12, 1957, January 15-17, 1958.

Symposia attended by project personnel in the interest of the contract were

1. The Third Annual Interference Reduction Conference,
   Armour Institute, Chicago, February 26, 27, 1957,
2. IRE National Convention, New York, New York
   March 17-20, 1957,

3. Annual PGMTT Meeting, "Microwave Ferrites and Related Devices
   and Their Applications," New York, May 9-10, 1957, and

4. Third Annual Symposium of Aeronautical Communications, Utica,
   New York, November 6-7, 1957.
IV. MATHEMATICAL TECHNIQUES FOR EVALUATING TUBE INTERMODULATION CHARACTERISTICS

A. Introduction

The basic approach to determining the intermodulation characteristics of r-f amplifier tubes was a direct approach by measurement of the total characteristic using simulated interfering signal voltages. However, it was conceived that a better insight into the fundamental nature of these directly obtained intermodulation characteristics might be obtained from a more analytic technique that would identify the contributing components of the tube system. The reliability of this technique is primarily determined by the accuracy of the basic data derived from measurement of specific parameters of the transfer characteristic. The preciseness of these measurements is determined by the quality of the instrumentation available.

The aim of this technique was to investigate a possible high speed method of analyzing tubes, particularly with respect to their intermodulation characteristics. Also, it was expected that a useful tool might be developed to help design future tubes to meet particular specifications.

In this section there is described a program of tube evaluation techniques based upon well known methods of numerical analysis facilitated by high speed computers. Numerical data were derived from tube static values and intermodulation data were computed and compared with measured intermodulation data from low frequency tests where relationships between static and dynamic values were known.

It has long been known that vacuum tubes are nonlinear devices. It is the nonlinear characteristic of a tube which gives rise to harmonic production and frequency translation of signals by mixing. Many of our present day circuits depend on this nonlinearity. A few examples are: mixers in superheterodyne receivers, harmonic frequency multipliers, and some forms of modulators. In these
cases it is advantageous to accentuate certain orders of the nonlinearities present in vacuum tubes, for example, by selecting an optimum operating point. For amplification of a signal, however, it is desired that the tube be a linear device. Of course this cannot be realized and certain spurious responses such as third-order intermodulation may seriously degrade the usefulness of the tube as an amplifier. In locations or in systems where third-order intermodulation is the most serious form of interference it is advisable to bias the tubes so that the third-order curvature will be a minimum. To do this it is useful to know the third-order curvature as a function of bias.

B. Treatment of Amplifier Tubes

A typical plate current characteristic is shown in Figure 4.1. A power

Figure 4.1. Fundamental Components in a Tube Characteristic.
series representation of the curve is of the form

\[ i_b = \sum_{n=0}^{k} C_n c^n \]  

which is a Maclaurin's series. The plate current characteristic may also be expressed by

\[ i_b = \sum_{n=0}^{k} C_n (e_c - E_{co})^n \]  

This is a Taylor's series representation of the transfer curve expanded about \( E_{co} \). For each \( E_{co} \) there will be a different set of \( C_n \)'s, since

\[ C_n = \frac{1}{n!} \left. \frac{\partial^n i_b}{\partial e_c^n} \right|_{e_c = E_{co}} \]  

To determine the expressions for third-, fifth-, and seventh-order intermodulation in terms of the \( C_n \)'s a signal of the form

\[ e_g = E_1 \sin \omega_1 t + E_2 \sin \omega_2 t \]  

may be assumed at the input to tube. The total grid voltage, \( e_c \), then is

\[ e_c = e_g + E_{co} = E_1 \sin \omega_1 t + E_2 \sin \omega_2 t + E_{co} \]  

Substitution of Equation 4.5 in Equation 4.2 gives

\[ i_b = \sum_{n=1}^{k} C_n (E_1 \sin \omega_1 t + E_2 \sin \omega_2 t)^n \]  

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Expression 4.6 may be expanded and the terms of like frequency can be collected in the form

\[
i_b = \sum_{x=-k}^{k} \sum_{y=-k}^{k} [B(x,y) \sin(x\omega_1 t + y\omega_2 t) + D(x,y) \cos(x\omega_1 t + y\omega_2 t)] ,
\]

(4.7)

where \( B \) and \( D \) are functions of \( E_1, E_2, C_n \).

From Equation 4.7 the third-, fifth- and seventh-order intermodulation-frequency currents are

\[
B_{(2,-1)} \sin(2\omega_1 t - \omega_2 t),
\]

\[
B_{(3,-2)} \sin(3\omega_2 t - 3\omega_3 t), \text{ and}
\]

\[
B_{(4,-3)} \sin(4\omega_3 t - 3\omega_4 t) .
\]

(4.8)

The object now is to determine the values of the \( B_{(x,y)} \) 's. This can be done by selecting a value of \( k \) in Equation 4.7 and actually performing the indicated expansion. Expansion of Equation 4.7 for \( k = 12 \) has been performed, and the values obtained for the third-, fifth- and seventh-order coefficients are:

\[
3^{rd} \text{ order IM due to curvature through 11^{th} order} = B_{(2,-1)} =
\]

\[
C_3 \left( \frac{3}{4} E_1^2 E_2 + C_5 (\frac{5}{4} E_1^4 E_2 + \frac{15}{8} E_1^2 E_2^3) + C_7 (\frac{105}{64} E_1^6 E_2 + \frac{105}{32} E_1^4 E_2^5 + 3780/256 E_1^2 E_2^7 + 504/32 E_1^4 E_2^5) \right)
\]

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\[ + C_{11}(1155/512 E_1^{10}E_2 + 12705/1024 E_1^{2}E_2^{9} + 3465/128 E_1^{8}E_2^{3} \]
\[ + 11550/512 E_1^{4}E_2^{7} + 34650/512 E_1^{6}E_2^{5}) , \quad (4.9) \]

7th order IM = \( B_{(3,-2)} = \)
\[ C_5 (5/8 E_2^3 E_3^2 + C_7 (165/64 E_2^5 E_3^2 + 35/16 E_2^3 E_3^4) + C_9 (756/256 E_2^7 E_3^2 \]
\[ + 1266/256 E_2^3 E_3^6 + 630/64 E_2^5 E_3^4) + C_{11} (1155/256 E_2^9 E_3^2 + 1155/128 E_3^8 E_4^3 \]
\[ + 6930/256 E_2^7 E_3^4 + 3460/1024 E_2^5 E_3^6) , \quad (4.10) \]

7th order IM = \( B_{(4,-3)} = \)
\[ C_7 (35/64 E_3^4 E_4^3 + C_9 (252/128 E_3^6 E_4^3 + 680/256 E_3^4 E_4^5) + C_{11} (1155/256 \]
\[ E_3^8 E_4^3 + 6930/1024 E_3^4 E_4^7 + 6930/512 E_3^6 E_4^5) , \quad (4.11) \]

where
\( E_1 = \) interfering signal of frequency \( \omega_1 = \omega_0 + \Delta \omega, \)
\( E_2 = \) interfering signal of frequency \( \omega_2 = \omega_0 + 2\Delta \omega, \)
\( E_3 = \) interfering signal of frequency \( \omega_3 = \omega_0 + 3\Delta \omega, \)
\( E_4 = \) interfering signal of frequency \( \omega_4 = \omega_0 + 4\Delta \omega, \)
\( \Delta \omega = \) channel spacing, and
\( \omega_0 = \) desired signal frequency.

Experiment has shown that when the interfering signal levels are small a good approximation to the intermodulation distortion is
\[ B_{(2,-1)} = \frac{3^{rd}}{2^{nd}} \text{ Order} = 3/4 E_1^{2}E_2 C_3 , \quad (4.12) \]
However, $C_3$, $C_5$, and $C_7$ can be expressed as a function of the bias voltage alone by means of Equation 4.3. Hence to find the optimum bias for minimum intermodulation of the third-, fifth- and seventh-order it is only necessary to find the proper roots of

$$C_3 = f(E_{co}) = 0,$$  \hspace{1cm} (4.15)

$$C_5 = f(E_{co}) = 0,$$  \hspace{1cm} (4.16)

$$C_7 = f(E_{co}) = 0.$$  \hspace{1cm} (4.17)

Experimental results have shown that the most serious type of intermodulation is third-order intermodulation. These results have also indicated that $C_5$, $C_7$, \ldots $C_{2n-1}$ can be neglected with respect to $C_3$, so that the third-order intermodulation term can be approximated as $3/4 C_3 E_1^2 E_2$.

C. Treatment of Mixer Tubes

The mathematical analysis of intermodulation in mixers proceeds in a manner similar to that used above. For mixers the input to the grid is of the form

$$e_c = E_{co} + E_1 \sin(w_o + \Delta \omega)t + E_2 \sin(2\omega_o + 2\Delta \omega)t + E_{Lo} \sin(\omega_{Lo} t), \quad (4.18)$$

where $\omega_{Lo}$ is the local oscillator frequency.

Substituting Equation 4.18 into Equation 4.2 gives

$$I_b = \sum_{n=0}^{k} C_n [E_1 \sin(w_o + \Delta \omega)t + E_2 \sin(2\omega_o + 2\Delta \omega)t + E_{Lo} \sin(\omega_{Lo} t)]^n, \quad (4.19)$$
Expanding Equation 4.19 and collecting terms of like frequency results in

\[ i_b = \sum_{m=-k}^{k} \sum_{n=-k}^{k} \sum_{p=-k}^{k} \left\{ B(m,n,p) \sin[(m + n)\omega_o + (m + 2n)\Delta\omega + p\omega_{LO}]t + D(m,n,p) \cos[(m + n)\omega_o + (m + 2n)\Delta\omega + p\omega_{LO}]t \right\} \] \quad (4.20)

If the tube is being used as a mixer, the frequency component of Equation 4.20 that is of interest is the i-f frequency. Hence the term of interest is of the form

\[ D(m,n,p) \cos[\omega_o - \omega_{LO}]t, \text{ or:} \]

\[ D(m,n,p) \cos[\omega_{LO} - \omega_o]t. \] \quad (4.21)

However, the magnitude of the \( D(m,n,p) \) coefficient of either of these terms is the same, and hence a minimum of one coincides with a minimum of the other.

Comparing Equation 4.20 with the term

\[ D(m,n,p) \cos[\omega_o - \omega_{LO}]t , \]

it is seen that the two are equal when

\[ m + n = 1, \]
\[ m + 2n = 0, \text{ and} \]
\[ p = -1. \] \quad (4.22)

Solution of Equation 4.22 gives

\[ m = 2 \]
\[ n = -1, \text{ and} \]
\[ p = -1. \] \quad (4.23)
Consequently, the coefficient of interest in determining the magnitude of the fourth-order intermodulation product is $D(2,-1,-1)$. If the indicated expansion of Equation 4.19 is actually performed for a given value of $k$, it is found that $D(2,-1,-1)$ is a function of $C_4$, $C_6$, $C_8$ and higher even-order coefficients and also of the magnitudes $E_1$, $E_2$ and $E_{LO}$. Fortunately, $D(2,-1,-1)$ is given to a good approximation by

$$D(2,-1,-1) = \frac{3E_1^2E_2E_{LO}C_4}{2} . \quad (4.24)$$

But from Equation 4.3 it is seen that $C_4$ is a function of $E_{co}$ alone. Hence, the minimum value of $D(2,-1,-1)$ with respect to the grid bias occurs for that value of $E_{co}$ which is the proper root of

$$C_4 = f(E_{co}) = 0 . \quad (4.25)$$

For determination of intermodulation rejection in amplifiers $C_3$ must be known, and for mixers $C_4$ must be known. If $C_3$ or $C_4$ have zeros then the optimum bias for amplifier or mixer operation respectively will be at these zeros.

D. Methods of Determining the Curvature of the Transfer Curve

The investigations presented in Chapters V and VI show experimentally that both $C_3$ and $C_4$ have zeros or very deep minimums. To facilitate the proper selection of tubes and to correlate the experimental data, mathematical methods were investigated by which the characteristic of $C_3$ and $C_4$ could be determined. Several well known methods, when used as described in the literature, gave erratic and erroneous results. Two methods, however, were devised on this project by which the $C_3$ characteristic could be determined. One of the methods provides information concerning the zero of $C_4$. 
1. Methods of Obtaining the Transfer Curve

The first method made use of an analog computer. The transfer curve of an individual tube under test was plotted, along with its first and second derivatives, obtained electronically in the computer. The maxima of the second derivative corresponded to the zeros of the third derivative.

The second method was an extension of the method of Espley. The data used for this method were taken from the transfer curve obtained on the analog computer. Before the transfer-curve data were used they were smoothed by the application of a Tshebysheff-Polynomial. The smoothed data were then used in an 11-point system of the Espley method to yield the values of the $C_n$'s in Taylor's series expanded about a particular value of $E_{co}$.

Early efforts in this project to obtain the third-order curvature of a vacuum tube used static characteristics which were measured point by point. It was realized that some drift and reading errors existed in this type of data, and an attempt was made to smooth the experimental curves by generating a least-squares polynomial approximation with an IBM 650 digital computer. Some smoothing was accomplished, but when the least-squares curve was differentiated (to obtain the Taylor series coefficients) the results were very erratic and misleading. A search was then made for a better experimental method of obtaining a transfer curve and for a better method of deriving a polynomial approximation to fit the transfer curve.

A method of obtaining a transfer curve was developed which made use of an analog computer and its associated equipment. The grid voltage of the tube being studied was swept from cutoff to zero bias by a voltage that increased linearly with respect to time. The output current of the tube was plotted versus time, and conversion of the time scale to bias voltage gave the desired transfer curve,
which was found to be very smooth. Three runs of a transfer curve were made with each of several tubes, and the repeated curves of each set exactly overlapped.

This method lent itself to electronic differentiation of the output current or transfer curve. It has been shown that the value of the third derivative at a particular bias point, when divided by $3!$, is equal to the third-order coefficient of a Taylor's series expanded about that bias point. For an analytic curve a maximum of the second derivative will occur for the same bias value as a zero of the third derivative or, correspondingly, a zero of the third-order coefficient of Taylor's series. Thus a knowledge of the second derivative can be used as a check on experimental and mathematical data on third-order intermodulation. This proves fortunate, since an inherent degradation of the signal-to-noise ratio exists in electronic differentiation, and the noise level after the second derivative was found to be too high to allow a third differentiation to be successfully accomplished. The analog computer program for obtaining the transfer curve and its derivatives is given in Appendix XII-A.

To preserve the advantage of the smooth curves obtained on the analog computer, it was necessary to read values at the various points very closely. This was accomplished by using a low power calibrated microscope. The reading error was estimated to be about $\frac{1}{4}$ percent of the smallest scale division of the graph paper, or about the width of the plotted line.

2. Functions for Approximating and Smoothing the Transfer Curve

The previously mentioned unfavorable results with methods appearing in the literature can be partially attributed to small unavoidable reading errors in the data. Most of these methods use difference equations and are thus very susceptible to errors in the data. It was assumed that these methods might yield reliable results if applied to a smoothed data curve that approximated
the transfer characteristic. This led to an investigation of methods for approximating a curve whose value was known only at a finite number of points.

Three possible types of approximations are (1) exponential series, (2) transcendental series, and (3) power series.

The shape of the transfer curve indicates that it might be approximated by an exponential series. Unfortunately no satisfactory method of an exponential approximation of a curve was found in the literature.

A Fourier series approximation of the curve was attempted. The basis of this method is the simulation of a transfer curve by the leading edge of a pseudo square wave. The axis was shifted to obtain even symmetry. A ten-term approximation to the transfer curve by this method was not a close enough fit to be used in obtaining the $C_n$'s. Since little improvement could be obtained with the addition of a few more terms, more favorable forms of approximation were sought.

A review of the literature on approximating functions showed that many methods of power series approximation existed. One of the best known of these, the least-squares method, was tried. A program written for the IBM 650 in the PALS language system existed in the library of the Rich Electronic Computer Center at Georgia Tech. This program is capable of finding an nth degree least-squares polynomial from any M observations provided $n > M > 26$. The residues between the data and the polynomial approximation at the input points are also provided. These residues were found to be very small. However, when the computed fifth-, seventh- and ninth-degree polynomials were each differentiated three times to obtain equivalent power series coefficients, no correlation existed between the derivatives. Furthermore, none of these gave results which agreed with experimental third-order intermodulation tests or analog computer data. Trials with other polynomial approximating routines also showed that even
though very good approximating curves could be obtained it was not possible to
differentiate the polynomial expressions analytically and obtain reliable results.
The basic reason for this was that the approximation was not of the same order as
the true curve. It is believed that the transfer curve cannot be expressed as a
finite power series.

The library of the Rich Electronic Computer Center contained a routine for
approximating a curve with a fifth-degree polynomial. This program (written in
the FACS language\textsuperscript{5} for the IBM 650) gave a much closer fit to the transfer curve
than did the least-squares method, and when used in conjunction with Espley's
method gave results which agreed fairly well with experimental data and with
results obtained from the analog computer. The limitation of this program to a
fifth-degree polynomial was felt to be a drawback, since there was no way of
knowing if higher order approximations of this type would give still better re-
sults.

A set of data points, suitably normalized, was programmed for obtaining a
Tschebysheff-Polynomial\textsuperscript{6} approximation to a curve. Routines for finding fifth-,
seventh-, and ninth-degree fits were formulated in the Bell General Purpose
Language.\textsuperscript{7} These routines calculated the approximating polynomial, evaluated
the polynomial for a given increment, and yielded the residues at these points.
The residues that were obtained were very small; the largest was approximately
equal to the maximum error in the initial reading of the transfer curve. Appli-
cation of the Espley method to these Tschebysheff-Polynomials showed a seventh-
degree fit of this type to be preferable to the fifth-degree fit or to the fifth-
degree system fit. Indeed, the seventh-degree Tschebysheff-Polynomial fit was
found to be better than the ninth-degree Tschebysheff-Polynomial fit even though
the residues for the ninth-order polynomial were less than those of the seventh.
The reason conjectured was that the slope of the curve as well as its magnitude is an important element. The constraint of the ninth-order curve to a close fit at a discrete number of points caused the slope of the ninth-degree approximating curve in relation to the true curve to be in greater error than the slope of the seventh-degree approximation. It is assumed that both the slope and the magnitude of the seventh-order curve were closer to true curve than they were in the fifth-degree polynomial.

The original tables of argument for the seventh-degree Tshebysheff-Polynomial are included in Appendix XII-A and the programs used for these are contained in one master program for obtaining $C_n's$, also shown in Appendix XII-A.

3. Evaluation of Power Series Coefficients

Evaluation of the power series coefficients by means of differentiation of a polynomial and by electronic differentiation have been mentioned earlier. A method proposed by Espley was investigated. The Espley method considers the operation of a tube at a bias, $E_{co}$, with a small signal, $e_g$, applied. Thus operation is over only a small part of the transfer curve. In Figure 4.2 the signal amplitude and the portion of the transfer curve over which operation takes place is greatly accentuated. The current at $E_{co}$ is $I_{bo}$ which is designated $I_{\frac{N+1}{2}}$, with the currents $I_1$, and $I_N$ being the minimum and maximum currents respectively in each cycle. $N$ is an odd number. The signal voltage is divided into $N-1$ increments, $\Delta e_g$, and the output current is measured at $E_{co} - K\Delta e_g$ where $K$ ranges from 0 to $\frac{N-1}{2}$. It is assumed that the operation of the tube about $E_{co}$ can be approximated by an $n th$ order Taylor's series expanded about $E_{co}$. Thus a set of equations for $I_1, I_2 - - - I_N$ takes the form

$$I_1 = C_0 + C_1\left[+ \Delta e_g\left(\frac{N-1}{2}\right)\right] + C_2\left[+ \Delta e_g\left(\frac{N-1}{2}\right)\right]^2 + \ldots + C_N\left[+ \Delta e_g\left(\frac{N-1}{2}\right)\right]^N$$
\[ I_2 = C_0 + C_1 \left[ + \Delta \epsilon \left( \frac{N-3}{2} \right) \right] + C_2 \left[ + \Delta \epsilon \left( \frac{N-3}{2} \right)^2 \right] + \ldots + C_N \left[ + \Delta \epsilon \left( \frac{N-3}{2} \right)^N \right] \]

\[ I_{N+1/2} = C_0 + C_1 + \ldots + C_N \]

\[ I_N = C_0 + C_1 \left[ - \Delta \epsilon \left( \frac{N-1}{2} \right) \right] + C_2 \left[ - \Delta \epsilon \left( \frac{N-1}{2} \right)^2 \right] + \ldots + C_N \left[ - \Delta \epsilon \left( \frac{N-1}{2} \right)^N \right]. \]  

(4.26)

Figure 4.2. Fundamental Tube Characteristic Components Used in Espley's Relations.
This set of equations can be solved for the $C_n$'s in terms of the currents. For $N = 11$ the formulas are shown below:

$$C_0 = I_6,$$

$$C_1 = \frac{1}{725760 \Delta e_g} \left\{ 576(I_{11} - I_1) - 7200(I_{10} - I_2) + 43200(I_9 - I_3) - 172800(I_8 - I_4) + 604800(I_7 - I_5) \right\},$$

$$C_2 = \frac{1}{3628800(\Delta e_g)^2} \left\{ 576(I_{11} + I_1) - 9000(I_{10} + I_2) + 72000(I_9 + I_3) - 432000(I_8 + I_4) + 3024000(I_7 + I_5) - 5311152 I_6 \right\},$$

$$C_3 = \frac{1}{725760(\Delta e_g)^3} \left\{ -820(I_{11} - I_1) + 10088(I_{10} - I_2) - 58428(I_9 - I_3) + 209712(I_8 - I_4) - 289392(I_7 - I_5) \right\},$$

$$C_4 = \frac{1}{3628800(\Delta e_g)^4} \left\{ -820(I_{11} + I_1) + 12610(I_{10} + I_2) - 97380(I_9 + I_3) + 524280(I_8 + I_4) - 1401960(I_7 + I_5) + 1926540 I_6 \right\},$$

$$C_5 = \frac{1}{34560(\Delta e_g)^5} \left\{ 13(I_{11} - I_1) - 152(I_{10} - I_2) + 783(I_9 - I_3) - 1872(I_8 - I_4) + 1938(I_7 - I_5) \right\},$$

$$C_6 = \frac{1}{3628800(\Delta e_g)^6} \left\{ 273(I_{11} + I_1) - 3990(I_{10} + I_2) + 27405(I_9 + I_3) - 98280(I_8 + I_4) + 203490(I_7 + I_5) - 257796 I_6 \right\}.
\[ C_7 = \frac{1}{120960(\Delta e_g)^7} \left\{ -5(I_{11} - I_1) + 52(I_{10} - I_2) - 207(I_9 - I_3) + 408(I_8 - I_4) - 378(I_7 - I_5) \right\}, \]

\[ C_8 = \frac{1}{3628800(\Delta e_g)^8} \left\{ -30(I_{11} + I_1) + 390(I_{10} + I_2) - 2070(I_9 + I_3) + 6120(I_8 + I_4) - 11340(I_7 + I_5) + 13860(I_6) \right\}, \]

\[ C_9 = \frac{1}{725760(\Delta e_g)^9} \left\{ (I_{11} - I_1) - 8(I_{10} - I_2) + 27(I_9 - I_3) - 48(I_8 - I_4) + 42(I_7 - I_5) \right\}, \]

and

\[ C_{10} = \frac{1}{3628800(\Delta e_g)^{10}} \left\{ I_{11} + I_1 - 10(I_{10} + I_2) + 45(I_9 + I_3) - 120(I_8 + I_4) + 210(I_7 + I_5) - 252(I_6) \right\}. \]

A program was written in the Bell General Purpose Language, which yielded reliable values for \( C_1 \)'s, \( C_2 \)'s, and \( C_3 \)'s corresponding to forty different bias points. Data needed for the program consisted of fifty evaluations from the seventh-degree Tschebysheff Polynomial approximation which was described above.

E. Results

The 6AF4, 6AJ4, 6AN4, 6BC4, 6BQ7A, 6BY4, 6J4, 417A, and the 6386 vacuum tubes were selected as typical VHF and UHF tubes. The transfer curve, along with its first and second derivatives, for a typical tube of each type was run on the analog computer. Then the tube was tested to determine its third-order intermodulation characteristic and a selected group was tested to determine the fourth-order intermodulation characteristics. The third-order characteristic
is associated with third-order intermodulation in amplifiers. The fourth-order characteristic is associated with third-order intermodulation in mixers.

The transfer curve data were read and put into a program which (1) found a seventh-degree Tschebycheff-Polynomial approximation to the curve, (2) evaluated the polynomial at fifty values of bias, (3) computed the residues at the fifteen input data points, and (4) then computed the desired $C_n$ ($C_1$ or $C_2$ or $C_3$) at forty bias values. Approximately 3 minutes is required to run this program after the Bell General Purpose System is read into the computer. The computer will automatically repeat the program when a new set of data is available at the input device. A set of typical results for the third-order intermodulation characteristic is shown in Figure 4.3. This figure shows the transfer curve for a 6AF4A tube, its second derivative as obtained on the analog computer, $C_2$, as obtained mathematically, $C_3$ also as obtained mathematically, and the third-order intermodulation characteristic as obtained from independent experimental tests on the tubes. $C_2$ was found to be exactly equal to $1/2$ the second derivative, as predicted from the theory. The maximum third-order intermodulation was found to occur at exactly the zero of $C_3$ and at the maximum of $C_2$, also as predicted from theory. This shows that the bias for maximum third-order intermodulation rejection can be found from either $C_2$ or $C_3$. Several tubes (6AJ4, 6AN4, 6BC4, 6EX7A, 6J4, 417A, and 6386) with equally good correlations and a few with slightly poorer results are shown in Appendix XII-B, Figures 12.3 through 12.9.

$C_4$ was not directly obtainable by this method, but even as the maximum of $C_2$ shows the zero of $C_3$, so does the maximum of $C_3$ show the zero of $C_4$. Both fourth-order intermodulation and fourth harmonic rejection tests were run on some of the tubes. The bias voltages for maximum fourth-order intermodulation and fourth harmonic rejection were compared with the bias voltage for the maximum of $C_3$, and the correlation is apparent in the results shown in Table 4.1.
COMPOSITE CHARACTERISTICS OF DISTORTION COEFFICIENTS AND INTERMODULATION REJECTION

6AF4A NO. 1

\[ E_b = 135V \]
\[ E_f = 6V \]

\[ C_2 = \frac{d^2 I_b}{de^2}/2! \]

INTERMODULATION REJECTION

\[ C_3 = mu/(\text{volt})^2 \times 10^{-2} \]

3RD ORDER IM REJECTION - db

PLATE CURRENT \( I_b \) - ma

GRID BIAS - volts

Figure 4.3. Composite Characteristics of Distortion Coefficients and Intermodulation Rejection for 6AF4A.
### TABLE 4.1
COMPARISON OF BIAS VOLTAGES FOR MINIMUM FOURTH-ORDER PRODUCTS

<table>
<thead>
<tr>
<th></th>
<th>DETERMINED EXPERIMENTALLY</th>
<th>DETERMINED MATHEMATICALLY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias Voltages</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for Maximum Fourth</td>
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<td></td>
<td>Harmonic Rejection</td>
<td></td>
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<tr>
<td></td>
<td>Bias Voltages</td>
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</tr>
<tr>
<td></td>
<td>for Maximum Fourth-Order</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intermodulation Rejection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bias Voltages</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for Maximum C₃</td>
<td></td>
</tr>
<tr>
<td>417A No. 7</td>
<td>2.52</td>
<td>- -</td>
</tr>
<tr>
<td>6HJ4 No. 8</td>
<td>2.71</td>
<td>- -</td>
</tr>
<tr>
<td>6BY4 No. 5</td>
<td>1.03</td>
<td>- -</td>
</tr>
<tr>
<td>6BJ7A No. 7</td>
<td>3.10</td>
<td>3.11</td>
</tr>
<tr>
<td>6AN4 No. 12</td>
<td>1.70</td>
<td>2.05</td>
</tr>
<tr>
<td>6AF4 No. 1</td>
<td>(+)</td>
<td>3.6</td>
</tr>
<tr>
<td>6386 No. 7(++)</td>
<td>- -</td>
<td></td>
</tr>
<tr>
<td>6386 No. 8</td>
<td>3.13</td>
<td>3.45</td>
</tr>
<tr>
<td>6AJ4 No. 7</td>
<td>2.78, 1.65 (+)</td>
<td></td>
</tr>
</tbody>
</table>

(+) Fourth harmonic too low to be measured.
(++) Tube failure.

F. Conclusions

Figure 4.4 shows the transfer curve and first four derivatives of three hypothetical tubes. It can be seen that slight changes in the shape of the transfer curve can drastically affect the values of C₁, C₂, C₃ and C₄. It can be seen that the second tube has by far the best third-order characteristic. It has a zero at low bias (high gain) and the values of C₃ near the zero are very small for a large range of voltage. Closer attention to the C₃ and/or C₄ characteristic in the design of new tubes might yield a very superior third-order rejection capability.

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Figure 4.4. Hypothetical Tube Characteristics and Their Derivatives.
An unexpected result of the comparison shown in Figure 4.4 is that since a tube with a linear characteristic cannot be built, one which appears to have an approximately linear characteristic (the first tube in Figure 4.4) may have worse intermodulation characteristics than a tube with a more parabolic shape (the second tube in Figure 4.4). This can be seen by comparing Tubes 1 and 2.

The methods described in this chapter for finding $C_3$ might be very useful in their present form in the design of low intermodulation tubes. The mathematical method for finding $C_3$ could be refined by linking the analog computer, which would measure the tube's transfer curve, directly to the digital computer by an analog-to-digital converter. This would eliminate the time consuming process of reading data off the transfer by use of a microscope.

The UHF transfer characteristics of an amplifier tube will differ from its low frequency transfer characteristic because of the influence of various factors which become noticeable at UHF. These factors are transit time loading, lead inductance, and stray coupling and produce gain instability and input and output impedance variations.\(^{16}\)

Transit time loading produces an equivalent displacement in the low frequency transfer characteristic and results in the current, corresponding to a given grid voltage reading a different value at UHF (usually smaller). This effect could be the reason why an apparent shift in the bias for class A operation between low frequency and UHF condition was observed in the laboratory.

Lead inductance in a grounded grid amplifier causes the "grounded" electrode to not be perfectly grounded. Thus in this type of amplifier energy which flows through the plate grid capacitance, $C_{P_g}$, appears across the inductance between the grid electrode and ground and consequently produces a change in the input characteristic of the amplifier. The principal results are an effective change
in the transconductance value of the tube and an influence on the phase and magnitude of the input impedance.\textsuperscript{17}

When the influence of both transit time loading and lead inductance are considered, the results of the technique of biasing for maximum third order intermodulation rejection are greatly altered at UHF. Low frequency tube parameters may be so completely masked by these high frequency factors that theoretical prediction of the UHF intermodulation characteristics from low frequency parameters is unreliable. The fact that there was poor correlation between the UHF third order intermodulation rejection characteristic of Figure 12.23 and mathematically derived characteristics, $C_3$, of Figure 4.3 is the result of the influences discussed above. These results however do not invalidate the mathematical technique described in this chapter since the results of computations were based upon initial values from the low frequency transfer characteristics. If the UHF transfer characteristics of the tube type involved in the above figures were known data could have been derived that would have correlated closer with the laboratory measurements. Facilities were not available to carry out measurements to obtain the UHF transfer characteristics on tubes tested. There is an instrument in existence now which appears to provide good facility for obtaining transfer function data from tubes at UHF.\textsuperscript{18}
V. INTERMODULATION CHARACTERISTICS OF AMPLIFIER TUBES

A. Introduction

The recommendation that amplifier tubes be operated with fixed bias adjusted at a point corresponding to maximum intermodulation rejection was based on a preliminary survey of one or two tubes of a small number of different types. Also in that survey only the third-order intermodulation rejection was noted and therefore there was no information available on the relative magnitudes of the higher order products. One of the tasks of the current contract was to make a broader survey among the currently available UHF tubes to provide information on their intermodulation rejection characteristic including the third-, fifth- and seventh-order products. This information was to show the variation of these characteristics with bias and to determine whether or not an optimum bias could be specified for each tube type when the condition of maximum intermodulation rejection is considered. It was also to reveal the influence of bias variation on these characteristics caused by tube aging and other tube parameters.

Fundamental theory on which this work is based has been presented in Chapter IV. The basic hypothesis there developed is that the coefficient, $C_n$, of the power series,

$$i_b = \sum_{n=0}^{k} C_n (e - E_{co})^n,$$

(5.1)

(which describes the tube's transfer characteristic, illustrated in Figure 4.1) is a function of the grid bias, $E_{co}$. It was further shown that the $C_3$, $C_4$, $C_5$, etc. each had a characteristic as a function of bias and that each had one or more zero points in the normal operating region of the tube. This implies that the characteristic of a particular order of intermodulation for a tube is influenced by the function of the power series coefficients.
A distinction should be made at this point between terms that have been used in Chapter IV and terms which will be used here. The various orders of coefficients in the power (Taylor's) series are associated with and identify the various orders of curvature possessed by the transfer characteristic. The "order" of intermodulation interference is established primarily by the frequency groups which give rise to it. An intermodulation order is related not only to the same order of coefficient in Taylor's series but also to orders of coefficients higher in the series. Thus it was shown by Expression No. 4.8 that third-order intermodulation may be derived from terms higher than, and in addition to, $C_3$, the third-order coefficient.

There are various kinds of intermodulation but usually because of sufficient receiver selectivity only a few kinds need be considered and these only include the odd orders. The order of the kind of intermodulation being considered here is identified by the sum of the absolute values of the coefficients, $M$ and $K$, of the interfering frequencies in groups of the form

$$ (M\omega_n + K\omega_{n+1}) , $$

where $n$ represents the "channel" position number of each interfering frequency referenced from the channel of the desired frequency, $\omega_o$. Thus third-order intermodulation is derived from all terms in the power series containing the frequency groups whose coefficients, in the expression

$$ 2\omega_1 - \omega_2 = \omega_o $$

$$ M = 2 $$

$$ K = -1 $$

are

$$ |M| + |K| = 3 . $$
The channel spacing necessary is

$$\Delta \omega = \omega_2 + \omega_3 = \omega_0 + \omega_1$$  \hspace{1cm} (5.4)

Fifth-order and seventh-order intermodulation are defined by

$$3\omega_2 - 2\omega_3 = \omega_0 \quad \left| |3| + |-2| = 5 \right.$$  \hspace{1cm} (5.5)

and

$$4\omega_3 - 3\omega_4 = \omega_0 \quad \left| |4| + |-3| = 7 \right.,$$

respectively. Channel spacing necessary for each case is

$$\Delta \omega = \omega_2 + \omega_3 = \frac{\omega_0 + \omega_2}{2} \quad \text{(fifth order)}$$

and

$$\Delta \omega = \omega_3 + \omega_4 = \frac{\omega_0 + \omega_3}{3} \quad \text{(seventh order)}$$  \hspace{1cm} (5.6)

Figure 5.1 illustrates these various frequency positions and the channel spacing.

Figure 5.1. Spectral Distribution of Frequencies Giving Rise to Odd-Order Intermodulation.
Measurements were made on 13 different types of UHF and VHF tubes. All of the types tested were triodes since most r-f amplifier sections encountered in UHF receiver design utilize this tube configuration. A few preliminary measurements on pentodes revealed intermodulation characteristics of a form similar to those obtained for triodes.

The technique of measurement was based on the two-signal method of intermodulation tests. Frequencies of the interfering signals were set relative to the desired frequency according to the order of intermodulation wanted. Voltage amplitudes of these frequencies were set equal to each other in all cases. This particular voltage relationship was established from the observation that it represented a serious condition that could be encountered in multiple equipment installations.\(^9\)

Determination of the value of intermodulation rejection from measurements on tubes was specified by the instrumentation facilities available. One definition of intermodulation rejection of an amplifier is given by

\[
\text{IM Rejection (db) } = 20 \log\left(\frac{\text{Input Amplitude of Interfering Signals}}{\text{Input Amplitude of Desired Signal}}\right),
\]

when the desired signal produces an output indication equal to the intermodulation output indication.

A second definition is

\[
\text{IM Rejection (db) } = 20 \log\left(\frac{\text{Output Amplitude of Desired Signal}}{\text{Output Amplitude of Intermodulation}}\right),
\]

when the input amplitude of both the interfering signals and the desired signals are equal.
Tests were made on tubes in two frequency regions. Initial measurements were at low frequencies in the range from 25 kc to 75 kc. Later measurements were carried out at 100 mc and 300 mc on some of the tubes checked at low frequency.

Low frequency measurements were done first primarily because facilities were not initially available for UHF measurement. An important purpose of the low frequency measurements, however, was the need for information to help interpret UHF measurements. Tube parameters obtained at low frequencies provide the possibility for scaling these values to represent high frequencies values.

B. Low Frequency Measurements

1. Types Tested

Table 5.1 shows the quantity of each of the tube types that were subjected to measurements at low frequency.

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Quantity Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>6AF4</td>
<td>11</td>
</tr>
<tr>
<td>6AJ4</td>
<td>5</td>
</tr>
<tr>
<td>6AM4</td>
<td>5</td>
</tr>
<tr>
<td>6AN4</td>
<td>5</td>
</tr>
<tr>
<td>6BC4</td>
<td>5</td>
</tr>
<tr>
<td>6BQ7</td>
<td>5</td>
</tr>
<tr>
<td>6BY4</td>
<td>4</td>
</tr>
<tr>
<td>6J4</td>
<td>12</td>
</tr>
<tr>
<td>6J4WA</td>
<td>6</td>
</tr>
<tr>
<td>EC80/6Q4</td>
<td>5</td>
</tr>
<tr>
<td>417A</td>
<td>6</td>
</tr>
<tr>
<td>5876</td>
<td>6</td>
</tr>
<tr>
<td>6299</td>
<td>4</td>
</tr>
<tr>
<td>6386</td>
<td>5</td>
</tr>
</tbody>
</table>

2. Measurement Procedures and Equipment

A block diagram of the setup for low frequency measurement of intermodulation characteristics is shown in Figure 5.2. The input portion of the
system operated at an impedance level of 500 ohms. The frequencies, $F_A$ and $F_B$, were adjusted according to a prescribed channel spacing and order of intermodulation. Frequency $F_A$ was always in the frequency channel nearest $F_o$, the desired frequency, and $F_B$ was in the channel farthest removed. Several frequency combinations were tried before the one in the above system was chosen. The frequencies for the various orders of intermodulation were:

Third order

$$F_A = 37 \text{ kc}, F_B = 47 \text{ kc}, F_o = 27 \text{ kc}$$

Fifth order

$$F_A = 47 \text{ kc}, F_B = 57 \text{ kc}, F_o = 27 \text{ kc}$$
Seventh order

\[ F_A = 47 \text{ kc}, \quad F_B = 67 \text{ kc}, \quad F_0 = 27 \text{ kc} \]

A low pass filter was used to prevent the second harmonic of \( F_A \) from mixing with the fundamental of \( F_B \) before being applied to the tube under test. To prevent interaction between the signal sources that would cause spurious intermodulation, an isolation bridge network was connected between the generators. Circuit details of this network are shown in Figure 12.42 in Appendix XII-C.

Grid bias for the tubes was supplied from a battery source and was adjusted to particular values by an accurate ten-turn potentiometer. The bias value was read from the dial of the potentiometer. Plate power was supplied to the test chassis by a well regulated source. An additional voltage regulator was built into the test chassis and a means was provided in the circuit to adjust the plate voltage to any desired value. The plate load impedance utilized in all measurements was 100 ohms except where noted differently. A constant voltage transformer was used to supply heater power for the tubes being tested. A schematic of the circuits built into the test chassis is shown in Figure 12.41 of Appendix XII-C.

To prevent the interfering frequencies from generating additional intermodulation in the wave analyzer a highly selective bandpass filter was used in the output of the test chassis. It provided a selectivity characteristic having a 60-db bandwidth of 10 kc. The low frequency receiver, RHL-5, provided some additional selectivity but primarily was used to increase sensitivity of the system. It was estimated that the dynamic measuring range of the system was about 100 db above 10 microvolts.

For purposes of making the technique of measurement clear, the procedure for measurement of third-order intermodulation rejection characteristic with
this system is outlined as follows:

1. The adjacent channel interfering signals, $F_A$ and $F_B$, are set at 37 and 47 kc, respectively, and their amplitudes are adjusted to the same levels, as indicated by the VTVM at the input to the tube under test.

2. The wave analyzer and TRF receiver are adjusted to give a response at 27 kc since the above frequency combination will produce this value for third-order intermodulation $(2F_A - F_B)$.

3. The plate and heater potentials having been previously adjusted to prescribed fixed values, the bias is adjusted and a minimum reading (dip in meter deflection) is noted on the wave analyzer. The bias for the point of minimum intermodulation is recorded.

4. A single frequency of 27 kc is applied in the place of the two signals, $F_A$ and $F_B$, at the input of the tube. This single frequency causes a reading on the wave analyzer meter. The input level of this signal is then adjusted until the reading of the meter is the same as the minimum reading caused by intermodulation in (3) above.

5. The reading on the VTVM at the input to the tube under test is noted. The ratio of the initial reading in (1) above to this last reading, expressed in decibels, is the maximum third-order intermodulation rejection of the tube.

6. Adjusting the bias in discrete steps each side of the point of minimum will provide data for additional values of intermodulation rejection. From these data a characteristic curve may be constructed showing the variation of rejection with bias.
Measurement of the fifth- and seventh-order intermodulation rejection values are also made by the above procedure. The majority of the tests were made with an input signal level for each interfering signal of 0.5 volts. Other values were used for observing certain effects and information on these effects is reported below.

Aging the tubes to observe the effect on their intermodulation characteristics was done on a laboratory built aging rack that permitted running two groups of different types simultaneously. Six different types were subjected to aging for periods of 60 hours and 145 hours.

3. Typical Data

Data were obtained to represent the intermodulation characteristics as a function of:

1. grid bias,
2. order of the intermodulation,
3. signal level,
4. anode voltage,
5. aging effects, and
6. plate load effects.

Figure 5.3 shows a typical plot of intermodulation rejection versus grid bias for one tube type. Generally the fifth-order and seventh-order rejection values are small in comparison to the third-order value and therefore a more useful presentation of the various orders is shown in Figure 5.4. Additional data on other tube types are presented in similar form to those in the preceding figure in Figures 12.10 to 12.22 of Appendix XII-B.

The effect of signal amplitude on the bias point of maximum third-order rejection is shown in Figure 5.5 for several types.
Typical Intermodulation Rejection Characteristics for 417A Tube Showing the Relationship Between the Different Orders (Represented by Tube No. 7)

- $E_b = 150$ volts
- $E_f = 6.4$ volts
- $E_1 - E_2 = 0.5$ volts

Figure 5.3. Typical Intermodulation Rejection Characteristics for 417A Triode.
Figure 5.4. 6J4WA Low Frequency Intermodulation Rejection.
A measurement was made to determine the influence of larger plate load impedances. Substituting a 5.0-mh inductance for the 100-ohm resistor, a 500-ohm load impedance was obtained. The 500-ohm value was determined by the input impedance of the filter network following the amplifier. The results of this measurement are shown in Figure 5.6 for the Tube Type 6B44 No. 6.

Influence of plate voltage on the third-order intermodulation rejection characteristic as a function of bias for the Type 6J4 No. 10 is shown in Figure 5.7 for three different voltage values. The range of bias adjustment for each plate voltage was limited to a small region around the point of maximum intermodulation rejection.
THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTIC
6BC4 NO. 6

COMPARISON OF 100 OHM PLATE IMPEDANCE WITH 500 OHM
INDUCTIVE IMPEDANCE

Figure 5.6. Influence of Plate Load on Third-Order Intermodulation Rejection.
Figure 5.7. Influence of Plate Voltage on Third-Order Intermodulation Rejection.

Tables 5.2 and 5.3 present results of aging measurements on several groups of different tube types. These results show the relative change in bias for maximum intermodulation rejection after a given number of hours of operation at normal conditions. Table 5.2 shows the results on a 60-hour run on five different types. Table 5.3 shows the results of an additional 85-hour aging period on the group of 6J4 listed in Table 5.2 and also the results on a different type not included in the above table.

4. Discussion of Results

It is noted in Figure 5.4 that each tube of the group has a point of maximum rejection on its intermodulation rejection characteristic. Each tube shows a particular bias value where this maximum occurs; however, there is a
<table>
<thead>
<tr>
<th>Tube Type</th>
<th>Tube No.</th>
<th>Before Aging</th>
<th>After Aging</th>
<th>Change in Bias After Aging</th>
</tr>
</thead>
<tbody>
<tr>
<td>6386</td>
<td>6</td>
<td>-2.77</td>
<td>-2.95</td>
<td>+6.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-2.35</td>
<td>-2.34</td>
<td>-0.4</td>
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<tr>
<td></td>
<td>9</td>
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<td>-2.36</td>
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<td>6A74</td>
<td>6</td>
<td>-1.24</td>
<td>-1.61</td>
<td>+30.0</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-2.07</td>
<td>-2.30</td>
<td>+11.0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-1.42</td>
<td>-1.47</td>
<td>+3.5</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-1.54</td>
<td>-1.61</td>
<td>+4.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-1.45</td>
<td>-1.47</td>
<td>+1.4</td>
</tr>
<tr>
<td>6J4WA</td>
<td>3</td>
<td>-1.98</td>
<td>-2.08</td>
<td>+5.0</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-1.85</td>
<td>-1.92</td>
<td>+3.8</td>
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<td></td>
<td>8</td>
<td>-1.71</td>
<td>-2.07</td>
<td>+21.0</td>
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<td></td>
<td>9</td>
<td>-1.86</td>
<td>-1.72</td>
<td>-7.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-1.71</td>
<td>-2.05</td>
<td>+20.0</td>
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<tr>
<td>6AF4A</td>
<td>1</td>
<td>-6.40</td>
<td>-5.99</td>
<td>-6.5</td>
</tr>
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<td></td>
<td>2</td>
<td>-8.37</td>
<td>-7.39</td>
<td>-11.6</td>
</tr>
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<td></td>
<td>11</td>
<td>-7.46</td>
<td>-7.50</td>
<td>+2.1</td>
</tr>
<tr>
<td>6J4</td>
<td>2</td>
<td>-1.52</td>
<td>-1.44</td>
<td>-5.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-1.85</td>
<td>-1.88</td>
<td>+1.6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-1.58</td>
<td>-1.66</td>
<td>+5.0</td>
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<td></td>
<td>8</td>
<td>-2.00</td>
<td>-1.87</td>
<td>-6.5</td>
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<td></td>
<td>10</td>
<td>-1.67</td>
<td>-1.75</td>
<td>+4.8</td>
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<td>11</td>
<td>-1.88</td>
<td>-1.82</td>
<td>-3.2</td>
</tr>
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<td></td>
<td>12</td>
<td>-1.75</td>
<td>-1.68</td>
<td>-4.0</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-1.44</td>
<td>-1.47</td>
<td>+2.0</td>
</tr>
</tbody>
</table>
TABLE 5.3

EFFECTS OF TUBE AGING ON BIAS VALUE FOR MAXIMUM
THIRD-ORDER INTERMODULATION REJECTION
(145-Hour Run)

<table>
<thead>
<tr>
<th>Tube Type</th>
<th>No.</th>
<th>Before Aging</th>
<th>60-Hour Run</th>
<th>145-Hour Run</th>
<th>Percent Change in Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tube No.</td>
<td>Bias (Volts)</td>
<td>IM Rej. (Db)</td>
<td>Bias (Volts)</td>
</tr>
<tr>
<td>6J4</td>
<td>2</td>
<td>-1.52</td>
<td>-1.44</td>
<td>-1.39</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-1.85</td>
<td>-1.88</td>
<td>-1.91</td>
<td>80</td>
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<td></td>
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<td>-1.65</td>
<td>91</td>
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<td></td>
<td>8</td>
<td>-2.00</td>
<td>-1.87</td>
<td>-1.87</td>
<td>83</td>
</tr>
<tr>
<td>10</td>
<td>-1.67</td>
<td>77</td>
<td>-1.75</td>
<td>-1.58</td>
<td>84</td>
</tr>
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<td>11</td>
<td>-1.88</td>
<td>73</td>
<td>-1.82</td>
<td>-1.88</td>
<td>62</td>
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<tr>
<td>12</td>
<td>-1.75</td>
<td>87</td>
<td>-1.68</td>
<td>-1.72</td>
<td>62</td>
</tr>
<tr>
<td>13</td>
<td>-1.44</td>
<td>83</td>
<td>-1.47</td>
<td>-1.49</td>
<td>75</td>
</tr>
<tr>
<td>6BC4</td>
<td>1</td>
<td>-1.89</td>
<td>-1.95</td>
<td>-1.855</td>
<td>77</td>
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<tr>
<td></td>
<td>2</td>
<td>-1.975</td>
<td>-1.91</td>
<td>-1.915</td>
<td>68</td>
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<td></td>
<td>3</td>
<td>-1.29</td>
<td>-1.79</td>
<td>-2.24</td>
<td>97</td>
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<td>4</td>
<td>-1.98</td>
<td>-2.07</td>
<td>-2.06</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-1.96</td>
<td>-1.96</td>
<td>-1.92</td>
<td>89</td>
</tr>
</tbody>
</table>

A good probability that not many of the tubes in a group will have the same bias point. Some types that were tested showed a much larger spread in these bias points than is indicated in the above figure. The group in this figure represents one of the better groups having a small percentage spread. Table 5.4 shows the evaluation of the spread in bias points for maximum intermodulation rejection in each tube type group. Five types, 6AJ4, 6AM4, 6J4, 6J4WA and 6386, had spread percentages less than 25 percent.

Manufacturing tolerances, which are acceptable to specifications of amplifier designs for normal operation, would appear by the above results insufficient.
TABLE 5.4
EVALUATION OF SPREAD IN BIAS POINTS FOR MAXIMUM INTERMODULATION REJECTION
(Interfering Signal Level = 0.5 Volt)

<table>
<thead>
<tr>
<th>Tube Type*</th>
<th>Average Maximum Rejection Bias (Volts)</th>
<th>Total Spread of Bias Values (Volts)</th>
<th>Percent Total Variation Relative to Average Bias (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6AF4</td>
<td>7.5</td>
<td>5.54</td>
<td>74</td>
</tr>
<tr>
<td>6AJ4</td>
<td>1.5</td>
<td>.31</td>
<td>20</td>
</tr>
<tr>
<td>6AM4</td>
<td>.97</td>
<td>.20</td>
<td>20</td>
</tr>
<tr>
<td>6AN4</td>
<td>.79</td>
<td>.85</td>
<td>108</td>
</tr>
<tr>
<td>6BC4</td>
<td>1.8</td>
<td>.69</td>
<td>38</td>
</tr>
<tr>
<td>6BQ7</td>
<td>1.01</td>
<td>.54</td>
<td>53</td>
</tr>
<tr>
<td>6J4</td>
<td>1.72</td>
<td>.41</td>
<td>24</td>
</tr>
<tr>
<td>6J4WAA</td>
<td>1.97</td>
<td>.36</td>
<td>18</td>
</tr>
<tr>
<td>417A</td>
<td>2.23</td>
<td>.90</td>
<td>40</td>
</tr>
<tr>
<td>5876</td>
<td>1.2</td>
<td>.55</td>
<td>46</td>
</tr>
<tr>
<td>6299</td>
<td>.62</td>
<td>.20</td>
<td>32</td>
</tr>
<tr>
<td>6386</td>
<td>2.2</td>
<td>.53</td>
<td>24</td>
</tr>
</tbody>
</table>

* Five tubes tested for each type.

for control of tube characteristics to insure specification of the stable bias value required in a design providing maximum intermodulation rejection. The variation of the intermodulation characteristic with bias change is seen to be large in the vicinity of the maximum rejection point. Therefore, if advantage is to be taken of the fact that maximum rejection can be obtained at a particular bias setting, two design factors must be considered: (1) that AVC cannot be used in this tube, and (2) that the stability of the bias source must be reasonably good (one percent or better). If some tolerance is permitted in the variation of intermodulation rejection then the requirement for bias stability is less stringent.
In so far as choosing the tube or tube type it is apparent from a study of the rejection characteristics, and in line with the conclusions of the previous chapter, that a tube with a rejection characteristic which has a rather wide valley (i.e., slow variation of value relative to the low point on the characteristic as bias changes) is the one desired. If a 0.25-volt total variation of bias is assumed, a comparison of the width of the third-order characteristics between types may be made. Table 5.5 shows a sample group of types that were studied from this standpoint. Also, the average of the maximum and minimum values of rejection are shown in this table from a study of the entire region of bias adjustment made during the tests.

**TABLE 5.5**

**EVALUATION OF LOW FREQUENCY THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS**

(Interfering Signal Level = 0.5 Volt)

<table>
<thead>
<tr>
<th>Tube Type*</th>
<th>Average Rejection Maintained for 0.25-Volt Variation (Db)</th>
<th>Average Value of Maximum Rejection for Group (Db)</th>
<th>Average Value of Minimum Rejection (Db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6AF4</td>
<td>78</td>
<td>88</td>
<td>50</td>
</tr>
<tr>
<td>6AJ4</td>
<td>51</td>
<td>83</td>
<td>25</td>
</tr>
<tr>
<td>6BC4</td>
<td>60</td>
<td>88</td>
<td>40</td>
</tr>
<tr>
<td>6BQ7**</td>
<td>46</td>
<td>68</td>
<td>35</td>
</tr>
<tr>
<td>6J4</td>
<td>53</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td>6J4WA</td>
<td>53</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td>417A</td>
<td>49</td>
<td>66</td>
<td>10</td>
</tr>
<tr>
<td>5876</td>
<td>48</td>
<td>68</td>
<td>40</td>
</tr>
<tr>
<td>6386</td>
<td>64</td>
<td>85</td>
<td>40</td>
</tr>
</tbody>
</table>

* Five tubes tested for each type.

** Excluding Tube No. 3
The group of 6A44's show the best performance in all three of the categories listed but when the spread of bias values for maximum rejection is considered for a group of these tubes its performance is not attractive. It was noted during tests on these types, as well as on others, that the maximum rejection points occurred in the bias region where the rated plate dissipation was being exceeded. Next to the 6AF4, the 6BC4 and the 6386 appear to give good results. The spread of maximum rejection bias points in these two types are much less than for the 6AF4. The type 6386 is a remote cutoff triode r-f amplifier tube that was developed to alleviate the problem of adjacent channel interference in airline duplex communication. The basis of design of this type is to obtain an essentially square-law transfer characteristic in which higher order curvature has been held to a negligible value. The 6386 was intended as a replacement for the prototype 5670 in circuits where the 5670 is being used. Figure 5.8 shows the average transfer characteristics of the above two types and in addition the characteristic of the type 6BQ7.

Ideally, an amplifier tube possessing a truly linear characteristic would eliminate the production of interference within the tube. Practical realization of such a tube has not been attained. The other approach suggested by the results above is the development of amplifier tubes with a truly square-law characteristic. This provides at least for elimination of intermodulation which is here the interference of primary concern. The other distortion products which are generated do not constitute a serious interference problem since the frequencies resulting from the parent off-channel frequencies fall well outside the pass band of the r-f amplifiers involved. The intermodulation rejection characteristic of such a tube would in reality not exist since its value would be infinite. However, if a tube were developed with a transfer characteristic
Figure 5.8. Average Transfer Characteristics for 6BQ7, 5670, and 6386. The curves closely approaching a square-law function, the rejection characteristic would probably possess a point of maximum value that would be quite broad with respect to bias variation.

Figure 5.3 and Figure 5.4 show characteristics of higher order intermodulation products. The first figure is representative of the manner in which each of the orders act with bias change. It also permits a study of the relation of the higher orders to the third-order characteristic. In most of the cases of other tube types the maximum rejection bias value for the fifth- and seventh-order correlated closely with the bias for maximum third-order rejection. The
seventh-order rejection values in every type were equal to or greater than the maximum value of the third-order rejection.

A study of the region where a condition of maximum third-order intermodulation rejection occurs in relation to the manufacturers recommended operating conditions for Class A shows that five types of those tested have good correlation between the two conditions. In Figure 5.4, for example, the 6J4 bias for maximum third-order intermodulation rejection is about 1.72 volts and the bias for Class A operation is 1.5 volts.

The family of intermodulation characteristics shown in Figure 5.7 above has some interesting features which are noteworthy. One observation is that the width of the valley of the characteristic widens as the plate voltage increases. This factor was noted in almost every type tested and indicates that the higher order curvature of the tube's transfer characteristic is decreasing, causing it to become more nearly square law in its function. Another observation is that the maximum rejection value of intermodulation increases somewhat as plate voltage increases. Only a limited bias voltage range was utilized in each case but it appears fruitful to carry the investigation of plate voltage effects further and observe the nature of the extremities of the intermodulation rejection characteristic.

A plate impedance increase by a factor of five on the tube in Figure 5.6 did not appreciably affect the shape of the intermodulation characteristic or the magnitude of its maximum rejection point. Also, it was interesting to note that the 500-ohm impedance was inductive and yet produced no significant differences in the results above. A reactive load generates an elliptical load characteristic in the tube's transfer function; however, this fact did not appear to make any difference in the rejection characteristics obtained for this condition as compared to those obtained with a pure resistive load.
Important in the application of the technique of adjusting the bias of a tube to obtain maximum intermodulation rejection is how long this condition of maximum rejection will remain. Aging characteristics presented in Table 5.2 and 5.3 indicate that changes in bias associated with maximum rejection are appreciable in some tubes. However, the changes observed in most of the tubes because of aging effects were much less in value than the initial maximum rejection bias differences that exist between tubes in a given type group. A greater number of tubes listed in the tables above maintained their bias within 5 percent of the initial value. Extending the aging period from 60 hours to 145 hours did not produce appreciable change in the variation noted in the first period. It is concluded that this effect may be neglected after an initial aging period which appears necessary to stabilize the tube's characteristic.

Under actual operating conditions all signals fluctuate in magnitude and therefore Figure 5.5 reveals the influence of these conditions as they affect the intermodulation rejection characteristics of different types of tubes. Ideally a tube should possess such a characteristic that shows at least no change in the bias value corresponding to maximum rejection condition as the signal levels change. The 6A14 and the 6386 approach this ideal property very closely.

C. High Frequency Measurements

1. UHF Measurements

A comparison of several tube types was made with respect to intermodulation rejection at UHF. In order to make this comparison, a standard measurement system was developed.

   a. Measurement System and Techniques. Figure 5.9 is a block diagram of the standard measurement system used in all UHF intermodulation measurements. Two interfering signals are simulated by signal generators $F_A$ and $F_B$. Results
from early UHF intermodulation measurements indicated that intermodulation was taking place within the signal sources due to insufficient isolation between the generator outputs. To provide isolation between the generators, a hybrid ring was constructed. The circuit details and physical dimensions of the hybrid ring and an associated balance network are shown in Figure 5.10. With the balance network disconnected and no load (Terminals 2 and 4 open) there is a 29-db loss from Terminal 1 to 3 at 290 and 295 mc. With the load connected to Terminal 2 and the balance network connected to Terminal 4, the variable capacitor in the balance network is adjusted for maximum attenuation between Terminals 1 and 3 at 292.5 mc. The loss across the hybrid ring at 290 mc and 295 mc is greater than 40 db. (Changes in the load cause this loss to vary, but it is never less than 40 db.) The loss from Terminal 1 to 2, and from Terminal 3 to 2, is 3 db (measured at 290 and 295 mc). The isolation between Terminals 1 and 3 is measured to be 30 db or greater from 270 to 335 mc. The 10-db pad prevents load changes from affecting the balance of the hybrid ring. A cavity filter in the unit under test is tuned to the desired (intermodulation) frequency, \( F_0 \), and provides selective attenuation of the interfering frequencies, \( F_A \) and \( F_B \). The output indicator is an r-f voltmeter tuned to \( F_0 \). Signal generator, \( F_0 \), provides a signal at the desired frequency for gain measurements. The 6-db pad reduces the signal level to the desired value and prevents load changes from affecting the output.

It was necessary to construct a number of different test sockets to accommodate the various tube types. For this requirement a standard test circuit, indicated as the "unit under test" in Figure 5.9, was constructed to use the test sockets. The tube under test was operated as a grounded grid amplifier with an output circuit consisting of a capacity tuned coaxial cavity. A schematic of the
Figure 5.9. Block Diagram – UHF Measurement System.

Figure 5.10. Isolation Element for UHF Intermodulation Measurements.
circuit used for all tube types is shown in Figure 5.11. (Note different biasing arrangement for Type 6299 tube.) The frequency characteristics of the cavity are such that it provides approximately 36 db discrimination between its center frequency and frequencies 5 mc away.

The two signal generators, $F_A$ and $F_B$, were set to 295 mc and 290 mc, respectively, to represent the interfering signals for third-order intermodulation. The hybrid ring was adjusted to give maximum isolation between the two generator outputs at 290 and 295 mc as described above. The signal generator, $F_0$, the coaxial cavity, and the output indicator were all tuned to 300 mc.

The system was checked for intermodulation generation in components other than the tube under test. First, the signal loss through the cavity and test circuit was measured at 290 and 295 mc, respectively. From this, the level of the interfering signals at the output indicator was determined with the test circuit and cavity in place. Then the test circuit and cavity were removed from the system and the output of each signal generator adjusted to deliver the same level to the output indicator as would have been present if the test circuit and cavity had been left in place. With the output indicator tuned to the third-order intermodulation frequency, $F_0$, negligible intermodulation was detected.

An additional test was made to determine if the second harmonic from the 295-mc signal generator was affecting the intermodulation readings. No change in the intermodulation output was detected, which indicated that there was insufficient second harmonic output from this signal generator to produce an error in tube measurement.

All measurements were made using a desired frequency of 300 mc and interfering frequencies at 290 and 295 mc (100 millivolts each). Plate, grid, and filament potentials are listed on the intermodulation rejection curves for each
A. GROUNDED-GRID AMPLIFIER CIRCUIT USED FOR UHF INTERMODULATION REJECTION MEASUREMENTS

B. BIASING CIRCUIT FOR TUBE TYPE 6299

Figure 5.11. Standard Test Circuit for UHF Intermodulation Measurements.
tube type. Tube types measured at UHF were: 6AF4A, 6AJ4, 6AM4, 6BC4, 6BY4, 6J4, 5876, 6299 and 6386.

As the grid bias was varied, values of intermodulation output were recorded at points where significant changes occurred. The gain of the amplifier at the various values of grid bias at which intermodulation outputs were recorded was obtained by switching the READ-CAL Figure 5.8 to the CAL position. The output was recorded from the output indicator, and since the input had been measured during the initial calibration, the gain (A) was readily calculated. The values of intermodulation output ($IM_o$) were converted to intermodulation rejection ($IM_r$) by the following equation:

$$IM_r = 100 + A - IM_o \quad \text{(All values are in decibels)}.$$ 

Intermodulation rejection versus grid bias curves for all tubes of the same type were plotted on a single graph. Grouping the individual tube curves on a single graph forms two limit curves which encompass the area occupied by the entire group. An average curve was obtained by averaging the intermodulation rejection values of all tubes of the same type at a given grid bias point.

b. Discussion of Results. Figure 5.12 shows resulting characteristics of third-order intermodulation measurements made on a group of 6J4 triodes. The individual tube curves made it apparent that greatest intermodulation rejection is obtained at low values of negative grid voltage (near maximum plate dissipation). This was found to be true for all tubes tested, except for the type 6386 tube, which exhibited an essentially constant intermodulation rejection. Furthermore, considerable variation of both the location and magnitude of maximum intermodulation rejection points between tubes of the same types is apparent. Also to be noted is the fact that the width of the bias interval within which the
THIRD-ORDER INTERMODULATION GAIN VS. GRID BIAS FOR FOUR 6J4 TUBES AT UHF

$E_b = 150 \text{ VOLTS}$

$E_{f1} = 6.4 \text{ VAC.}$

$F_1 = 295 \text{ mc., } 100 \text{ mv}$

$F_2 = 290 \text{ mc., } 100 \text{ mv}$

$F_{14} = 300 \text{ mc}$

Figure 5.12. UHF Gain and Intermodulation Rejection Characteristics for 6J4 Triodes.
intermodulation is near a maximum varies considerably between tube types. Table 5.6 gives an evaluation of the UHF measurements on several tube types that demonstrates the effect of bias variation on third-order intermodulation rejection. UHF intermodulation rejection characteristics on additional types are shown in Figures 12.23 to 12.36 in Appendix XII-B.

**TABLE 5.6**

<table>
<thead>
<tr>
<th>Tube Type*</th>
<th>Average Rejection Maintained for 0.25-Volt Variation (Db)</th>
<th>Average Value of Maximum Rejection (Db)</th>
<th>Average Value of Minimum Rejection (Db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6AJ4</td>
<td>73</td>
<td>73</td>
<td>50</td>
</tr>
<tr>
<td>6AM4</td>
<td>60</td>
<td>63</td>
<td>43</td>
</tr>
<tr>
<td>6BY4</td>
<td>58</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>6J4</td>
<td>62</td>
<td>70</td>
<td>48</td>
</tr>
<tr>
<td>6BC4</td>
<td>70</td>
<td>71</td>
<td>59</td>
</tr>
<tr>
<td>5876</td>
<td>87</td>
<td>100</td>
<td>60</td>
</tr>
</tbody>
</table>

* Five tubes tested for each type.

The limit curves, shown in Figure 5.13 for ten 6J4 tubes, represent the maximum and minimum values of intermodulation rejection that can be expected for particular bias values. The average curve is indicative of the distribution of the individual tube curves between the limits.

A fifth-order intermodulation check was made for each tube type. The co-axial cavity, output indicator, and signal generator, $F_o$, were tuned to 305 mc. The fifth-order intermodulation was recorded from the output indicator as the grid bias was varied. The gain was determined as in the third-order measurements.
AVERAGE THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS AT UHF TENT TYPE 6J4 UHF TRIODES

\[ E_b = 150 \text{ volts} \]
\[ E_f = 6.4 \text{ volts} \]
\[ F_1 = 295 \text{ mc} \]
\[ F_2 = 290 \text{ mc} \]
\[ F_{IM} = 300 \text{ mc} \]

Figure 5.13. 6J4 Average UHF Third-Order Intermodulation Rejection Characteristics.
The fifth-order intermodulation rejection was 20 to 40 db greater than the third-order rejection, for all tube types tested. Seventh-order was detected but no reliable measurements could be made and it was assumed that the level was at least 90 to 100 db below 0.1 volt.

Tube Types 6J4, 6299, and 6386 were checked to determine the effect of plate voltage on intermodulation rejection. Figure 5.14 shows the results obtained using different values of plate supply voltages for Tube Type 6299 which are typical of those tested. Results from these tests indicate that higher values of plate voltage give greater intermodulation rejection.

![Graph showing UHF Third-Order Intermodulation Rejection Obtained for Different Plate Voltages.](image-url)
2. VHF Measurements

   a. Measurement Techniques and Results. Measurements were made to obtain the third-order intermodulation rejection characteristics of a 6386 and a 6BQ7 at 100 mc. The 6BQ7 was chosen for this test because it represented a typical VHF tube in current use. The test was designed to show the improvement in intermodulation rejection in a tube with a remote cutoff transfer characteristic as compared to one with a sharp cutoff characteristic. Figure 5.15 presents the rejection characteristics of the above two types. Figure 5.16 shows the third-order intermodulation rejection characteristics for one of the 6386 tubes in the preceding figure and two Type 5670 triodes. Input voltages representing the interfering signals were set at 100 millivolts. Testing techniques were essentially the same as those used for UHF measurements. Details of special test circuit networks are shown in Figures 12.43 and 12.44 of Appendix XII-C.

   b. Discussion of Results. Although the improvement in rejection is not exceptional in the above comparison (Figure 5.15) it does point toward a method of interference reduction that should receive more serious consideration. The valley of the characteristic for Type 6386 is somewhat wider in the vicinity of its maximum rejection point than the valley of the characteristic for the 6BQ7. Of course, it is noted that the maximum rejection value of the 6386 is larger.

   A more significant demonstration of the effect of striving for a square-law characteristic is shown in Figure 5.16 between two types that are closely related in physical detail and circuit application. However, the 5670 is a sharp cutoff triode. Although it has as great a maximum rejection value as the 6386, the rapid changes in the rejection value as bias changes from these points are noticeably greater.
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GRID BIAS – volts

INTERMODULATION REJECTION CHARACTERISTICS
FOR TYPES 6386 & 6BQ7

\[ f_0 = 97.4 \text{ mc} \]
\[ f_1 = 92.4 \text{ mc} \]
\[ f_2 = 87.4 \text{ mc} \]

\[ E_b = 100V \]
\[ E_f = 6.3V \]

INTERFERING SIGNAL LEVEL 100 mv

- TUBE NO. 10 - 6386
- TUBE NO. 17 - 6386
- TUBE NO. 11 - 6386
- TUBE NO. 7 - 6BQ7

Figure 5.15. VHF Third-Order Intermodulation Rejection for 6BQ7 and 6386.
Figure 5.16. VHF Third-Order Intermodulation Rejection for 5670 and 6386.
A gain characteristic is shown for the 5670 in a test circuit in which there was actually a transmission loss. However, this characteristic reveals the fact that the condition of maximum intermodulation rejection occurred in a region where the gain was about 3 db below the maximum. A second maximum of smaller value does occur close to the point of maximum realizable gain.

D. Conclusions and Recommendations

Low frequency intermodulation rejection measurements showed third-order intermodulation to be more severe than either fifth or seventh order. The maximum rejection points on the fifth and seventh order characteristics were observed to occur very close to the maximum rejection point of the third-order characteristic in almost every tube tested.

Third-order intermodulation measurements showed that there was very little probability for any of the tubes in the same type group to have the same maximum rejection bias. Generally the bias value found in each type was close to the recommended bias for Class A operation.

Larger plate voltages were found to produce wider "valleys" in the third-order intermodulation characteristic in the vicinity of the maximum rejection point as compared to the characteristics at lower plate voltages. A noticeable increase in maximum rejection value was also observed.

Aging effects on the maximum third-order rejection bias were found to be small after an initial "baking in" period of 60 hours.

Two types showed their third-order rejection characteristics to be relatively independent of the amplitude of the interfering signals.

Fixed bias operation of a r-f amplifier tube is permissible when the upper limit curve is used as a design parameter. Using this procedure, the intermodulation rejection value obtained will be equal to or greater than the upper limit.
value. Greater values of intermodulation rejection may be obtained by the use of selected tubes, or adjustable bias, or a combination of both. In order to realize the maximum intermodulation rejection of a particular tube, it is necessary to adjust the bias so that the tube is operating at the point of maximum intermodulation rejection. Since this point differs from tube to tube it is possible to realize greater rejection by selecting tubes having greater values of intermodulation rejection. A combination of selected tubes and adjustable bias would permit an optimum intermodulation rejection to be realized.

Comparing the intermodulation rejection characteristics of the 6386 and the 6BQ7 in Figure 5.14 above, the following observations are seen:

1. Both types show a point of maximum rejection with respect to grid bias.
2. The rejection of the 6386 gets no worse than 50 db over the bias range tested whereas the rejection of the 6BQ7 may become 40 db or less.
3. For a one-volt bias change in the vicinity of the point of maximum rejection the 6386 may be varied from -1.25 volts to 2.25 volts and still maintain a rejection of at least 63 db. The best region for the 6BQ7 is between -1.4 volts and -2.4 volts where the minimum rejection is 48 db.

Comparing the UHF intermodulation rejection characteristics of a given tube with its low frequency characteristics poor correlation is observed between the grid bias points of maximum rejection. It was pointed out in Chapter IV that the differences found in the UHF measurements were principally from the influence of transit time loading and lead inductance. Types intended for UHF operation have been designed to minimize these influences on their operation. However it is noted that in some of these types the maximum rejection point on the intermodulation characteristic is difficult to locate. The pencil triode, type 5876, gave very good intermodulation rejection values at UHF compared to all other
types tested. In comparison the type 6299, whose basic construction is similar, gave very poor rejection values. The type 6AJ4 produced UHF intermodulation characteristics that compared more favorably with its low frequency characteristics than any of the other miniature plug-in types tested. This may have resulted from its tube design in which major attention was given to minimizing lead inductance. It is interesting to note that the basic design of the 6AJ4 evolved from the structure of the 6AF4 and that this structure was used in the initial development tests to determine the effect of lead inductance. In view of this relationship between the 6AF4 and 6AJ4 a comparison of their intermodulation rejection characteristics as shown in Figure 12.23 and Figure 12.24 respectively reveals the improvement in intermodulation rejection of the 6AJ4 that apparently results from better tube design.
VI. INTERMODULATION CHARACTERISTICS OF MIXER TUBES

A. Introduction

A study of interference problems in typical multichannel UHF receivers indicated the need for techniques to make mixers more interference resistant. The particular aims were to provide circuit performances with a better noise figure and better intermodulation rejection than that of the circuits used. The relatively poor selectivity and power gain of typical r-f amplifiers allows the mixer to contribute greatly to the overall noise figure and intermodulation rejection of a receiver. Although better r-f amplifier performance is the obvious and desirable solution, it is apparent that an optimum intermodulation rejection may only be achieved by improving both the r-f amplifier and the mixer.

The investigation on mixers in the current contract was concerned primarily with the study of the intermodulation characteristics of mixer tubes in various types of mixer circuits. This led to the investigation of these tubes as conventional (grid) mixers and also as less conventional type mixers such as the plate mixer and the inverted amplifier mixer.

The plate mixer was reported previously.\textsuperscript{1} The name is derived from the fact that the signal to be translated in frequency is applied in the plate circuit while the oscillator signal is applied in the grid circuit.

The grid mixer is a conventional circuit in which the signal to be translated in frequency and the oscillator signal are both applied in the grid circuit.

A triode tube may be used in an inverted amplifier mixer in which the oscillator signal is applied in the plate circuit and the signal to be translated in frequency is applied to the grid circuit. The translated frequency appears in the grid circuit as a result of the grid conductance being controlled by the plate voltage.
Ten tube types were tested for fourth-order intermodulation rejection in the circuits mentioned above. It was realized that some of the tubes were less adaptable to mixing than others. However, the basic study was to determine the relative intermodulation rejection characteristics of various tube types and the control of intermodulation by the operating conditions.

In Chapter IV a good correlation is shown between the results of the mathematical method for obtaining the bias voltage for maximum fourth-order intermodulation rejection in mixers and the bias voltages for minimum intermodulation as found by experiment.

The basic test circuit for measuring fourth-order intermodulation is shown in Figure 6.1. While measuring fourth harmonic distortion the bridge was not used, and the 16-kc low pass filter was removed. These tests clearly showed that the fourth-order curvature varied with bias in a manner that could be predicted from the slope variations of the $C_3$ characteristic.

**B. Plate Mixer**

1. **Low Frequency Measurements**

The circuits of Figures 6.2 and 6.3 were used for medium and low frequency intermodulation tests respectively while the circuit of Figure 6.4, was used for the UHF tests. A number of tubes, which included the following types: 6AF4, 6AM4, 6AN4, and 6AJ4, were tested. Considerable care was exercised in selecting the test frequencies and a study of the detector apparatus was made in each case to eliminate errors. These studies included such precautions as elimination of intermodulation within the wave-analyzer amplifiers, and the selection of frequencies to keep intermodulation product frequencies away from spurious response frequencies of the analyzers. Also, the input signal generators were sufficiently decoupled to eliminate intermodulation resulting from one
Figure 6.1. Mixer Intermodulation Rejection Test Setup.
Figure 6.2. Plate Mixer Circuit for Medium Frequency Intermodulation Measurements.

Figure 6.3. Plate Mixer Low Frequency Test Circuits.
Figure 6.4. Experimental UHF Plate Mixer and Test Circuit.
generator modulating the output stage of another. Typical data from these tests are shown in the graphs of Figures 6.5, 6.6, and 6.7. Conversion voltage amplifications varied between 0.1 and 0.5. The fourth-order intermodulation rejection of some tubes varied as much as 50 db with changes in bias. Rejections as great as 70 db were obtained with several tubes.

For most tubes tested the graphs of fourth-order intermodulation and the fourth harmonic as functions of bias had the same approximate shape. These variations are shown for some of the tests in the graphs of Figures 12.37 through 12.40 in Appendix XII-B.

2. High Frequency Measurements

The above tube types were also investigated in the test circuit of Figure 6.4 representing the UHF version of the plate mixer. Conversion amplification was found to vary between 0.3 and 0.4 when signal voltages varied between 300 millivolts and 25 microvolts. Conversion power loss was approximately 10 db, and intermodulation rejection varied between 69 and 70 db.

The mixer circuitry of the AN/GRR-7 receiver was changed as shown in Figures 6.8 to evaluate the performance with the plate mixer in use. The output circuitry of Figure 6.8 was altered as shown in Figure 6.9 to obtain a better match between the plate mixer and the first i-f stage. The data shown in Table 6.1 are typical of that obtained in actual receiver tests. An evaluation of the results is discussed in the concluding paragraphs of this chapter.

3. Discussion of Results

Many tube types had a fourth-order intermodulation rejection as a function of bias which varied as much as 30 to 50 db; however, the two 6AF6A tubes tested showed a variation of 10 db, with a minimum rejection of 60 db. Some of the tubes tested gave rejections as much as 70 db or more with signal voltages of 0.5 volts rms.
Figure 6.5. Plate Mixer Intermodulation Rejection Characteristic of 6AM4.

TABLE 6.1
PLATE MIXER IN AN/GRR-7 RECEIVER

<table>
<thead>
<tr>
<th></th>
<th>A-F &amp; R-F Gain Maximum (Microvolts)</th>
<th>R-F Gain Dial at 8 A-F Gain Maximum (Microvolts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise output at phone jack with no input signal</td>
<td>$2.2 \times 10^6$</td>
<td>$0.3 \times 10^6$</td>
</tr>
<tr>
<td>Minimum signal for detector output</td>
<td>2.05</td>
<td>7.4</td>
</tr>
<tr>
<td>Minimum signal for AVC threshold</td>
<td>54</td>
<td>650.</td>
</tr>
<tr>
<td>Signal-to-noise power ratio at AVC threshold</td>
<td>13.6</td>
<td>100.</td>
</tr>
<tr>
<td>Signal for $\frac{\text{signal} + \text{noise}}{\text{noise}} = 10 \text{ db}$</td>
<td>11.5</td>
<td>22.</td>
</tr>
</tbody>
</table>
Figure 6.6. Plate Mixer Intermodulation Rejection Characteristic of 6AN4.

Figure 6.7. Plate Mixer Intermodulation Rejection Characteristic of 6AF4.
Figure 6.8. Plate Mixer Substituted for Mixer in AN/GRR-7 Receiver.

Figure 6.9. Output Circuit Substituted for Transformer, T301, in Receiver.
The conversion amplification was less than unity in all cases and varied from approximately 0.1 to 0.5 depending on the tube, operating region, and input as well as output impedance transformations. The low conversion voltage amplification pointed out the need for an analytical study as an attempt to evaluate the conversion power loss. The expression describing the time varying transconductance of a conventional grid mixer may also be used to describe the time varying plate conductance of a plate mixer. Let

\[ g_p(t) = g_{po} + \sum_{n=1}^{\infty} g_{pn} \cos n \omega_o t, \quad (6.1) \]

where \( g_p(t) \) = time varying plate conductance,

\( g_{po} \) = constant term,

\( g_{pn} \) = Fourier coefficient of nth harmonic of fundamental component \( g_p(t) \), and

\( \omega_o \) = angular frequency of fundamental of \( g_p(t) \) or the local oscillator angular frequency.

The signal voltage input to the plate mixer can be represented as

\[ e_s = E(t) \cos \omega_g t, \quad (6.2) \]

where

\( e_s \) = time varying input signal,

\( E(t) \) = envelope variation corresponding to the modulation, and

\( \omega_g \) = angular frequency corresponding to the carrier.

If the input signal, \( e_s \), is effectively applied between plate and cathode of the mixer, then, assuming plate conductance to be independent of the signal
voltage, the plate current is

\[ i_p(t) = e_s g_p(t), \quad \text{(6.3)} \]

\[ = g_{po} E(t) \cos \omega_s t \]

\[ + [E(t) \cos \omega_s t] \sum_{n=1}^{\infty} g_{pn} \cos n \omega_o t. \]

The envelope time variations of \( e_s \) are very slow compared to \( \omega_s t \) or to \( n \omega_o t \), and \( E(t) \) may be replaced by a constant, \( E \). Then Equation 6.3 becomes

\[ i_p(t) = g_{po} E \cos \omega_s t + E \sum_{n=1}^{\infty} g_{pn} \cos \omega_s t \cos n \omega_o t \quad \text{(6.4)} \]

\[ = E[g_{po} \cos \omega_s t + \frac{g_{p1}}{2} \cos(\omega_s - \omega_o)t + \frac{g_{p2}}{2} \cos(\omega_s + \omega_o)t] \]

\[ + \frac{g_{p2}}{2} \cos(\omega_s - 2\omega_o)t + \frac{g_{p2}}{2} \cos(\omega_s + 2\omega_o)t \]

\[ + \ldots + \frac{g_{pn}}{2} \cos(\omega_s - n\omega_o)t + \frac{g_{pn}}{2} \cos(\omega_s + n\omega_o)t]. \]

In Equation 6.4 it will be noted that the terms within brackets are multiplied by the amplitude of the signal input to the plate of the plate mixer. In a similar analysis of a conventional grid-injection mixer it can be shown that the quantity \( E \) in Equation 6.4 would be replaced by \( \mu E \). This doubtless explains the lack of conversion gain in a plate mixer.

Equation 6.4 does not predict the mixer intermodulation behavior because of the assumption of independence of \( g_p \) as a function of signal voltage. It is only in the secondary effect of the input signal on tube parameters that nonlinear mixing occurs.
In order to verify the conductance approach a study on a 6AN4 was carried through. The plate conductance as a function of oscillator voltage was determined from tube characteristics. Then the dynamic conductance as a function of signal voltage was determined for two amplitudes of signal. Laboratory measurements verified the calculated dynamic conductances within reasonable accuracy. Further calculations using the calculated dynamic conductances indicated a conversion power loss of 12.2 db. This loss was due to the tube alone and did not include the losses in output and input circuitry. The above calculation was based on grid and plate polarizing potentials of \(-1\) volt, and 125 volts respectively, with an oscillator peak voltage of 1.2 volts and a signal of one-volt peak.

The input and output impedance problem for plate mixers is essentially the same as that for diode mixers. The external plate circuit impedances should be low at the angular frequencies \(\omega_0\) and \(\omega_s\) and should be adjusted for maximum power transfer at \(\omega_1 = \pm \omega_0 \pm \omega_s\), where \(\omega_1\) is the i-f frequency.

C. Conventional Mixers

1. Measurement Techniques

The basic circuit of Figure 6.10 was used to test a number of tubes as grid mixers. Precautions similar to those in the plate mixer test were taken in order that mixes outside of the mixer tube itself would be avoided.

2. Tubes Tested - Typical Data

A large number of tube types were tested as grid mixers. These included Types 6AN4, 6AM4, 6AP4, 6AJ4, and 6386. The principal study was to determine fourth-order intermodulation rejection characteristics of the mixer as a function of the bias voltage. Typical data of these tests are shown in the graphs of Figures 6.11 and 6.12.

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Figure 6.10. Grid Mixer Test Circuit.

Figure 6.11. Grid Mixer Intermodulation Rejection Characteristic of 6AN4.
Figure 6.12. Grid Mixer Intermodulation Rejection Characteristic of 6AM4.
As predicted from tube tests the fourth-order intermodulation rejection was found to be very dependent on bias. The limit of the intermodulation rejection which could be measured by the equipment was approximately 60 db so that the values of bias for maximum rejection could not be found at low signal level. Rejections as great as 60 db were obtained with one-volt signals.

D. Inverted Amplifier Mixer

The circuit of Figure 6.13 was constructed and tested for conversion amplification and intermodulation rejection. This circuit is similar to the plate mixer in that the conductance of one element is varied by a potential change on another element. In this case the grid conductance is varied by the local oscillator voltage applied to the plate. A limiting factor in the use of this circuit is the allowable grid dissipation; however, conversion gain in general was found to be better with low grid currents. Tubes tested included Types 6AF4, 6AJ4, and 12B4A. The conversion amplification was found to be a few tenths, as it was in the plate mixers. However, the intermodulation rejection was found to be very poor. Intermodulation rejection varied from 15 to 30 db with 1.0-volt signals.

Figure 6.13. Inverted Amplifier Mixer for Intermodulation Measurements.
E. Conclusions and Recommendations

1. Plate Mixer

The test and study of this circuit indicates its practical value to be limited to large signal mixing where intermodulation may be a problem. The large conversion power loss is a disadvantage not easily overcome in that the loss must be made up in stages ahead of the mixer in order to preserve a good overall noise figure. This procedure then would decrease the overall intermodulation rejection of the receiver due to higher signal levels in the latter r-f stages.

The test of the plate mixer in the AN-GRR-7 receiver indicated a degradation of sensitivity by a factor slightly greater than three. Calculations similar to those carried out in Chapter VIII, indicated a noise figure of about 2000 for the receiver with the plate mixer which is 200 times greater than the noise figure of the receiver with the conventional mixer. It must be concluded that the selection of the plate mixer over the grid mixer for UHF receivers would not lead to optimum performance.

2. Conventional Mixers

Study and tests of these circuits indicated that intermodulation rejection may be controlled to a considerable extent by the proper selection of the tube and the bias point. When optimum conditions are realized the intermodulation rejection is comparable to that found in the plate mixer. The conversion amplification was found to be that given by the conventional theory outlined elsewhere in this report, and to be many times that realized in the other circuits tested.

Practical circuits for conventional mixers are more easily attained than the circuits of the less conventional types, in that the plate circuit impedance
is fixed tuned at the intermediate frequency and there are no additional impedances to be controlled in this circuit. The low conversion power gain of the less conventional types presents a greater problem in the realization of low noise figures for receivers in which they are used than does the conventional mixer. It appears that there is a need for tubes suitable for UHF mixers with better controlled characteristics than the best of those available at this time.
VII. LINEAR UHF ATTENUATORS

A. Introduction

When the individual stages of the r-f amplifier are operated at fixed bias to minimize intermodulation, the AVC function is removed from the r-f amplifier. To prevent overload of the final r-f stages when the incoming signal is large, the AVC function must be assumed by a controlled attenuator placed ahead of the receiver. It is necessary that the attenuator be linear for the range of input voltages expected so that it will not contribute intermodulation. It is also desirable that the attenuator have a very low minimum attenuation value so that it will not degrade the sensitivity of the receiver.

The manner by which linear attenuation serves to reduce intermodulation can be illustrated by the following examples. The limitation of the method is also pointed out.

To illustrate a case when improvement in intermodulation can be obtained by attenuation between antenna and receiver, assume:

(1) a desired signal at $f_0$ with an amplitude at the receiver antenna of 30 microvolts,
(2) undesired signals at $f_1$ and $f_2$, adjacent and alternate channel frequencies, of 100,000 microvolts each at the antenna,
(3) a receiver threshold sensitivity of 1.0 microvolts,
(4) third-order intermodulation rejection of 40 db in the receiver for 100,000 microvolt interference producing signals, and
(5) zero attenuation between the antenna and the receiver.

The ratio of the desired signal to the intermodulation interference, both at frequency $f_0$, is 30:1000. The interference signal would control AVC in the receiver.
Next assume that 20 db linear attenuation is placed between the antenna and the receiver. The desired signal at the receiver input would then be 3 microvolts and the undesired signals would be 10,000 microvolts. The intermodulation rejection of the receiver, however, is 80 db for the 10,000 microvolt interference producing signals. The ratio of the desired signal to the interferences is increased then to 3:1. In this case, the linear attenuation enables the desired signal to control the receiver AVC.

To illustrate a case when improvement cannot be obtained with linear attenuation, assume:

1. a desired signal at $f_o$ of only 3 microvolts, and
2. the same assumptions as those numbered from 2 through 5 in the first example.

Without linear attenuation, the ratio of desired signal to interfering signal is now 3:1000.

When 20 db linear attenuation is inserted between the antenna and the receiver, the ratio of the desired signal to the undesired signal is only 0.3:1. Furthermore, the desired signal is below the receiver sensitivity.

Two experimental model attenuators have been developed on this project. One consists of a short section of coaxial air line with a sleeve of ferrite material over the center conductor. The degree of attenuation is controlled by varying the degree of magnetization of the ferrite sleeve. The second variable attenuator consists of a metal vane in the coupling port of a two-cavity tunable preselector, Collins Model No. 156C-2. The degree of attenuation is controlled by varying the size of the opening between the cavities, i.e., by moving the metal vane in or out of the coupling port.
B. The Ferrite Attenuator

A simple controlled UHF attenuator consists of a coaxial air line with a ferrite sleeve over the inner conductor. The attenuation of the line can be controlled by causing the strength of a steady magnetic field about the ferrite to vary with the AVC voltage. Figure 7.1 is a sketch of the elements of such an attenuator.\(^{11,12}\) It will be noted that the ferrite insert as sketched is relatively short, that it almost fills the space between inner and outer conductors, and that the control field is perpendicular to the axis of the line. Figures 7.2 and 7.3 show the characteristics of attenuators based on the configuration of Figure 7.1.\(^1\)

It was noted above that a desirable feature of the attenuator is a low value of minimum attenuation. It was thought that the use of a thin-walled tube
Figure 7.2. Average Attenuation Curves for Ceramic No. 7.

Figure 7.3. Average Attenuation Curves for Ferramic H.
should yield an attenuator with a lower minimum insertion loss than the thick-walled insert of Figure 7.1, because the thin-walled tube would constitute a smaller discontinuity in the line. The work of other investigators also suggested that thin planar sections of ferrite in a radial configuration should be tried. A third configuration suggested was a tube tapering from thin walls at the ends to thick walls at the center.

Considerable effort was directed toward drilling thin-walled sleeves from solid-bar ferrite stock, but the material proved too brittle. The unsuccessful methods tried included drilling with a brass tube on a drill press, lapping on a lathe, and drilling with brass and stainless steel tubes on a supersonic vibration tool. A successful method finally adopted involved the reduction of the outer diameter of thick-walled tubes available as stock items with cast 1/8-inch center holes. In this method, the thick-walled tube was chucked in a lathe, and a Do-All attachment with a diamond wheel cutter was mounted on the tool holder. As the ferrite tube rotated in the lathe, the diamond wheel cutter, on automatic screw feed, reduced the outer diameter of the stock. The Do-All attachment was also used on a milling machine to slot the tubes.

The materials tested included Ferramic H, Ferramic Q, and TT-414. Experimental coaxial air lines and control solenoids were constructed to test the materials in various core configurations.

The arrangement of equipment for measuring the attenuation characteristics is shown in Figure 7.4. The characteristics of Ferramic H and TT-414 are shown in Figures 7.5 and 7.6. The characteristics of several different shapes of

* Supplier: General Ceramics Corporation, Keasbey, New Jersey.
** Supplier: Trans-Tech, Inc., Rockville, Maryland.
Ferramic Q material are shown in Figure 7.7, and the corresponding VSWR's are shown in Figure 7.8. The attenuation characteristics of Ferramic Q were the best of the materials tested.

It was thought that the high values of VSWR in Figure 7.8 were caused by incorrect ratios of inner- and outer-conductor diameters. Therefore three lines were constructed with diameter ratios of 2.5, 2.75, and 3.0, and further tests were made with various core configurations of Ferramic Q. The results of the tests are given in Figures 7.9 and 7.10, and photographs of the components of the experimental attenuators are shown in Figure 7.11. On the basis of the best combination of low VSWR, low insertion loss, high initial attenuation, and rapid decrease of attenuation with applied field, the choice would lie between Configurations No. 2 and No. 4 of Figure 7.10. Both of these core configurations and the air line and solenoid finally adopted are shown in the bottom photograph.
Figure 7.5. Attenuation Characteristics of Ferramic H Ferrite.

Air line: 20 cm, 50 ohm, General Radio 874—L20.
Center conductor: 0.245 in. dia.
Ferrite: 18-1/4 in. pieces, 0.330 in. outside dia.
Solenoid: 5-3/4 in. long, 3000 turns of No. 22 magnet wire.
Frequency: 250 mc
Figure 7.6. Attenuation Characteristics of TT-414 Ferrite.

Air line: 20 cm, outer conductor and connections of General Radio 874-L20.
Center conductor: 0.156 in. dia.
Ferrite: 1 piece, 5 in. long, 0.375 in. outside dia.
Solenoid: 5-3/4" in. long, 3000 turns of No. 22 magnet wire
Frequency: 250 mc
Figure 7.7. Attenuation Characteristics of a Coaxial Line Attenuator with Various Core Configurations.
of Figure 7.11. The core finally adopted is like Configuration No. 2 of Figure 7.10, except that the length of the thicker walled piece is 5.3 inches.

The variations of maximum and minimum attenuation values with frequency are shown in Figure 7.12.

The solenoid power required for minimum attenuation is about 85 watts. The iron yoke attenuator shown in Figure 7.13 was constructed in an effort to reduce the power required for minimum attenuation, but experimental comparison of the air solenoid and the iron yoke attenuators showed the former to be more desirable, as indicated in Figure 7.14. It will be noted that no significant saving in the power required for a one-db insertion loss was found with the iron yoke. Furthermore, over three times as much power was needed for an
Figure 7.9. Attenuation Characteristics of Coaxial Line Attenuator Using Only Ferramic Q.
Figure 7.10. Attenuation Characteristics of Coaxial Line Attenuator Using Different Core Configurations than Figure 7.9.
Figure 7.11. Components for Experimental Models of Coaxial Ferrite Attenuators.
Final Report, Project No. A-312

Figure 7.12. Frequency Characteristics of Ferrite Attenuator.

Figure 7.13. Iron Yoke, Transverse Field, Ferrite Attenuator.
Figure 7.14. Field Power versus Attenuation for Longitudinal and Transverse Magnetic Fields in Given Core Configuration.

attenuation of 20 db when the iron yoke was used, as compared to the air solenoid. Figure 7.15 is another comparison of the iron yoke and the air solenoid attenuators, with magnetizing field strength used as a basis of comparison. The curves of Figure 7.15 also indicate the superiority of the air solenoid configuration for the ferrite attenuator.

Figure 7.16 is a photograph of the air solenoid ferrite attenuator with its control amplifier and associated power supply. Schematics of the amplifier and power supply are shown in Figures 12.45 and 12.46 of Appendix XII-C.

No intermodulation was found to be generated in the ferrite attenuator for input signals up to 0.5 volts. The limit of sensitivity for measuring IM rejection was 95 db with the equipment used.
The attenuator was tested as an AVC element at the input to a GRR-7 receiver. Figure 7.17 shows the AVC characteristic of the GRR-7 receiver under two conditions: (1) unmodified and (2) with the ferrite attenuator AVC action replacing the normal AVC action in the r-f amplifier. The block diagrams in Figure 7.17 indicate the manner in which the ferrite attenuator action replaces the r-f AVC action.

Figure 7.18 is a curve showing the signal voltage entering the receiver as a function of the signal voltage entering the attenuator, and it indicates that the total range of the ferrite attenuator AVC effected a 40-db compression of input-signal voltage. The receiver r-f gain control was set at 8.3 on its dial.
Figure 7.16. The Ferrite Attenuator.
Figure 7.17. AVC Characteristics of a GRR-7 Receiver.
for the curves of Figure 7.18. Had the r-f gain control been fully advanced, the signal compression would have been about 45 db.

Several measurements were made at various points in the system to determine the responses to a sudden change of input-signal level. The results of the measurements are shown in Figure 7.19. Figure 7.19A shows the audio output for a 30-percent, 1000-cps modulated input. The input signal was first increased stepwise from about 0.1 to 100 millivolts, and then was decreased stepwise back to about 0.1 millivolt. The 60-cps ripple serves as a timing indication, and shows a total recovery time, including the overshoot, of about 0.125 second for the signal increase. If the overshoot is ignored, recovery time for the step increase was only about 0.08 second.
Figure 7.19. Transient Response of a GRR-7 Receiver with Different AVC Conditions.
Figure 7.19B shows the recovery for a step increase taken with a faster sweep so that the recovery times can be measured by counting cycles of the 1000-cps modulation.

For comparison, the responses to step-increase inputs to an unmodified receiver are shown in Figure 7.19C. It is seen that the ferrite attenuator increased the recovery time by 0.05 second for the 0.1-volt input step (if the overshoot is ignored).

The responses of the AVC amplifier, as measured at the junction of R356, R342, R314, R338, and C333 in the R-361A/GR receiver, are shown in Figure 7.20A. The longest response time for the unmodified receiver was for a decrease of input signal from 0.2 millivolt, and was about 0.1 second. Note, however, the very fast response of the unmodified-receiver AVC voltage to step increases of the input — a response time of 0.01 second or less. The effect of the longer time constant of the ferrite attenuator is reflected in the longer AVC voltage recovery times, as shown in Figure 7.20B. Coil current variations for step input-voltage changes are shown in Figure 7.20C.

The feedback capacitor, 0.02 mfd, shown in the schematic of the control amplifier, Figure 12.45 of Appendix XII-C, was found to be necessary to stabilize the system against low-frequency oscillation. This capacitor determines the response time of the attenuator when the latter is used as an AVC element.

C. The Mechanical Attenuator

A two-cavity tunable preselector, such as the Collins Model No. 156C-2 is a useful addition to the AN/GRR-7 and other UHF receivers. A mechanical attenuator, mounted in the coupling port between the two cavities of a Collins Model No. 156C-2, and actuated by the AVC voltage in the associated receiver, was developed during this contract.
Figure 7.20. Transient Waveforms of AVC Voltage in a GRR-7 Receiver.
Two means of controlling the degree of coupling, i.e., the size of the opening between the cavities, were examined. First, a circular disk pivoted about a vertical shaft was tried. The low moment of inertia of the pivoted disk and its mechanical simplicity were attractive. However, as shown in Figure 7.21 an intolerable amount of detuning was introduced.

Figure 7.21. Response Characteristics from "Butterfly" Vane in 156C-2 Coupling Port.

The second means of controlling the size of the port was by sliding a vane across the opening, as shown diagramatically in Figure 7.22. An exploded view of an attenuator based on the second method of closure is shown in Figure 7.23. The degree of detuning was less than that found for the pivoted disk, as is shown by comparing Figure 7.24 to Figure 7.21.
Figure 7.22. Attenuation Versus Aperture Size of Coupling Port in 156C-2 Filter.
2000 500 1000 1500
A
0° 30° 25° 225° 20° 15° 0°
ATTENUATION CHARACTERISTICS FOR VANE ATTENUATOR, FIRST MODEL, FOR VARIOUS ANGLES OF SWING, °
3db INSERTION LOSS:
200 kc DETUNING:

Figure 7.23. Mechanical Attenuator, Vane Element.

Figure 7.24. Attenuation Characteristics for Swinging Vane Attenuator.
A servo control amplifier, Figure 12.47 in Appendix XII-C, was constructed and combined with the mechanical attenuator. A photograph of the assembly is shown in Figure 7.25.

The servo-actuated mechanical attenuator was tested as an AVC element with the GRR-7 receiver. In Figure 7.26 the AVC characteristic of the unmodified receiver is compared with the characteristics of the receiver with the mechanical attenuator. Two curves are shown for the mechanical attenuator, corresponding to two settings of the receiver r-f gain control. Plots of the signal level entering the receiver versus the signal level entering the preselector were constructed from Figure 7.26, and are shown in Figure 7.27. The degree of compression impressed on an incoming signal before it reaches the first r-f amplifier is the difference between the curve of Figure 7.27 and the straight line.

Figure 7.28A shows AVC voltage responses of the unmodified receiver to step changes of input voltage. Figure 7.28B shows responses of AVC voltage when the mechanical attenuator replaced the r-f amplifier AVC action. Comparing the two figures shows that the servo system increased the transient recovery time to a maximum of 0.25 second, including the small final overshoot, or 0.20 second if the final overshoot is ignored. The recovery time for an increasing-step input is somewhat longer than the recovery time for a decreasing-step input. Recovery time for a decreasing step is only about 0.15 second. Figure 7.28C shows the transient recovery as an envelope on the 1000-cps output of the receiver. Again, the recovery time is about 0.25 second, and can be timed by the 60-cps ripple. Figure 7.28D shows the error signal in the servo amplifier corresponding to the second curve in Figure 7.28B.

D. Conclusions

Either the magnetically controlled ferrite coaxial attenuator or a servo-actuated mechanical vane attenuator can be used ahead of a receiver as an AVC
Figure 7.25. Mechanical Attenuator, Servo Drive and Coaxial Filter.
Figure 7.26. AVC Characteristics of a GRR-7 Receiver with a Mechanical Vane Attenuator.
element. Both require about 85 watts maximum power. Neither produces inter-
modulation from input signals as high as 0.5 volt.

The response time of the ferrite attenuator to a step change of input sig-

nal is about 0.08 second, which is about half the response time of the mechani-
cal attenuator. Maximum insertion loss for both attenuators is less than 3 db.

The mechanical attenuator performs better than the ferrite attenuator for
input signals of less than 0.1 volt, but the ferrite attenuator performs best for
input signals that exceed 0.1 volt, as can be seen by comparing Figures
7.18 and 7.27.

The attenuators are early laboratory models and are not optimum devices;
therefore the comparisons given here are not valid bases for recommending one
type of attenuator over the other.
Figure 7.28. Transient Waveforms in a GRR-7 Receiver with a Mechanical Attenuator.
The range of attenuation for the ferrite attenuator was 38 db at 225 mc. The range of AVC action in decreasing the gain of the r-f amplifier in the R-361A/GR receiver was only about 23 db. The range of the ferrite attenuator might therefore be reduced, with a consequent reduction of the power requirement to about 50 watts.

A thorough survey of available ferrites would probably reveal a better core material than the Ferramic Q used. Information furnished by manufacturers is not useful in selecting materials for use at UHF, and most of the data in the literature are for microwave frequencies. A note is included in the appendix, which further explores the necessary characteristics of ferrite materials to be used as UHF attenuators. It is pointed out in the appendix that a material which completely saturates in a field of 100 oersteds will, if it otherwise has the loss characteristics of Ferramic Q, require only 1/25 the magnetizing power of the Ferramic Q attenuator, or about 2 watts. This small power could be supplied by a one tube amplifier instead of the massive equipment of Figure 7.16.
VIII. APPLICATION OF INTERMODULATION REDUCTION TECHNIQUES

A. Introduction

Three ways to reduce intermodulation were explored: (1) operation of tubes at optimum, fixed bias voltages, (2) selectivity, and (3) linear attenuation of the incoming signals ahead of the receiver input.

Measurements were made of maximum third-order intermodulation rejection of four experimental r-f amplifier and mixer chassis, which employed different UHF tube types. Two of the experimental chassis were tested for intermodulation rejection of the r-f amplifiers alone, excluding the mixer. All four experimental chassis were then mounted in "outboard" fashion in the R-361/GR receiver, operationally replacing the receiver r-f amplifier-first mixer chassis. Each experimental chassis employed some variation of the improved r-f selective input network of Figure 8.1 which shows its response compared with the response of the original R361 receiver input network. Intermodulation rejection of the receiver, with the substituted experimental units, was then measured and the effectiveness of the improved input network in reducing intermodulation was noted.

Tests were made of the intermodulation reduction effects of (1) the ferrite attenuator as an AVC element ahead of the receiver, (2) a crystal filter as a replacement for the receiver 40-mc network, and (3) the Collins 156C2 coaxial-filter as a preselector.

Receiver noise figure measurements were made along with the intermodulation tests on the receiver, to evaluate the effects of the experimental units on receiver sensitivity.

B. Measurement Techniques

1. Intermodulation Rejection Tests

The first two experimental r-f amplifier-mixer chassis constructed were tested for maximum third-order intermodulation rejection of the amplifier
A. CIRCUIT CONFIGURATION

B. FREQUENCY CHARACTERISTIC

Figure 8.1. Selective R-F Input Network.
stages alone. The arrangement of equipment for the tests is shown in Figure 5.8. Maximum rejection was obtained by setting the bias voltages of the r-f amplifiers.

A block diagram which shows the arrangement of equipment for the third-order intermodulation measurements made with the four experimental chassis mounted in the receiver is shown in Figure 8.2. The similarity between Figure 8.2 and

Figure 8.2. Arrangement of Equipment for Testing the Application of Intermodulation Reduction Techniques.

Figure 5.8 is apparent. The discussion in Chapter V about the use of the hybrid ring and the attenuator pads for the prevention of undesired intermodulation signals is appropriate here also.

The two interference producing signals were at frequencies \( f_1 \) and \( f_2 \), removed respectively \( \Delta f \) above and \( 2\Delta f \) above the frequency, \( f_0 \), to which the
receiver was tuned. The levels of the signals at \( f_1 \) and \( f_2 \) were both set at a desired voltage, usually to correspond to 0.1 volt at the receiver input. The Empire Devices VTVM served to indicate the signal level. For 0.1 volt into the receiver the VTVM indication was 83 db above 1 microvolt, and the signal at the hybrid ring output was 103 db above 1 microvolt. The receiver input signal was nominally attenuated 3 db below the hybrid-ring signal level. The purpose of the 3-db pad was twofold: to isolate the elements in the measurement system and to permit evaluation of the intermodulation reducing effects of any off-resonance impedance mismatch which might characterize the input selective circuit of the unit under test. The attenuation pad made the test conditions more closely approximate the actual isolation conditions between the receiver and the interfering transmitters.

Either the AVC voltage of the receiver, or the detector output voltage, was used as a reference indication of the magnitude of the third-order intermodulation interference caused by the two signals at \( f_1 \) and \( f_2 \). The \( f_2 \) signal was then cut off, and the frequency of the \( f_1 \) generator was changed to \( f_0 \). The amplitude of the \( f_0 \) signal was adjusted to reproduce the AVC (or detector output) magnitude. The amount of reduction in decibels of the generator amplitude below that of \( f_1 \) and \( f_2 \) was recorded as the intermodulation rejection of the receiver.

The tests to determine third-order intermodulation reduction effects of the ferrite attenuator, the crystal filter, and the coaxial preselector were made in a manner similar to that outlined above. When the crystal filter replaced the 40-mc network, the receiver's second oscillator was modified to oscillate at 29 mc. (A crystal having a third overtone at 29 mc replaced the regular crystal, and an inductor of the proper value replaced the oscillator tank inductor.) The receiver i-f was left unchanged at 6 mc.
2. Noise Figure Measurements

The arrangement of equipment for noise figure measurements is shown in Figure 8.3. The method is based on "Standards on Electron Devices: Methods of Measuring Noise," Proc. IRE 41, pp. 890-896 (1953). The expression for average noise figure is

$$\bar{F} = \frac{Q_1}{Q_2 - Q_1} \frac{P_s}{KT_o B},$$  \hspace{1cm} (8.1)

where

- $\bar{F}$ = average noise figure,
- $Q_1$ = noise power output as read on the noise meter, for zero generator output, but with the generator connected to the receiver, and
- $Q_2$ = noise power output when the generator is set to deliver $P_s$ available signal power. For convenience $Q_2$ is made to be twice the value of $Q_1$, and then
  $$\frac{Q_1}{Q_2 - Q_1} = 1.$$
- $P_s$ = available signal power (see reference),
  $$= \frac{V^2}{4R_G},$$
- $V$ = Thevenin's equivalent open circuit voltage, at output of attenuator,
  $$= \frac{V_G}{5}$$ for a 20-db pad as shown in Figure 8.3,
- $R_G$ = resistive component of Thevenin's equivalent source,
  $$= 50 \text{ ohms},$$
- $V_G$ = indicated output of the signal generator of Figure 8.3,
- $K = 1.38 \times 10^{-23}$ joules per degree Kelvin, Boltzman's constant,
\[ T_0 = \text{temperature in degrees Kelvin, and} \]

\[ B = \text{noise bandwidth of the receiver in cycles per second.} \]

It should be noted that \( P_s \), the available signal power, is

\[ P_s = \left(\frac{V_G}{10}\right)^2 \frac{1}{R_G}, \quad (8.2) \]

and that an impedance match at the input is not necessary.

The noise bandwidth of the receiver was found from a receiver power versus frequency curve; a typical one is shown in Figure 8.4. The scales of both axes of Figure 8.4 are linear. A rectangle erected as shown on the peak value of the characteristic, with an area equal to the area under the curve, has a width corresponding to the noise bandwidth of the receiver. The base line for determining the area under the curve is the average noise level of the receiver.

In the IRE Standards mentioned above, it was stressed that the point at which the power is measured should be ahead of envelope or square-law detection, but that mixers may be regarded as linear frequency shifters and may precede the point of measurement. The power measurements on the receiver were made at the output of the i-f strip.

The noise figures of the unmodified receiver are given in Table 8.1 for three input frequencies.

Equation 8.1 can be reduced to a more tractable form, for when \( Q_2 = 2Q_1 \),

\[ F = \frac{(V_G)^2}{(100)(50)(290)(1.38 \times 10^{-23})B}, \quad (8.3) \]

\[ = \frac{(V_G)^2}{(2 \times 10^{-17})B}. \]
Figure 8.3. Equipment Arrangement for Measuring the Noise Figure of the GRR-7 Receiver.

Figure 8.4. Power-Frequency Characteristic of a R-361A/GR Receiver from the Input through the I-F Amplifier.
TABLE 8.1

NOISE FIGURES FOR THE GRR-7 RECEIVER

<table>
<thead>
<tr>
<th>Frequency (Mc)</th>
<th>Average Noise Figure (Db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>10.5</td>
</tr>
<tr>
<td>292</td>
<td>10</td>
</tr>
<tr>
<td>379</td>
<td>12</td>
</tr>
</tbody>
</table>

Estimated error: ± 1 db.

A bandwidth of 65 kc at the output of the 6-mc i-f amplifier may be assumed for the R-361/GR receiver. Then

\[
\overline{F} = (V_g)^2 \left(0.77 \times 10^{12}\right) . \tag{8.4}
\]

(An error of 25 percent in the bandwidth results in an error of only one decibel in the noise figure.)

Equation 8.4 shows the functional relationship between the R-361/GR receiver noise figure, \(\overline{F}\), and \(V_g\), the indicated generator output, for the arrangement of Figure 8.3. If there is an impedance match at the receiver input, \(V_g\) is ten times the receiver sensitivity for a signal-plus-noise to noise ratio of 2 at the output of the i-f amplifier. The inclusion of the factor 10 is necessary because of the 20-db pad between the generator and the receiver.

The relationship between noise figure and input sensitivity, eliminating the factor of ten in the voltage term, is

\[
\overline{F} = (V_{in1})^2 \left(0.77 \times 10^{14}\right) . \tag{8.5}
\]
for a signal-plus-noise to noise power ratio, \((S+N)/N\), of 2 at the i-f output. If the input signal is increased to make the ratio of \((S+N)/N = 10\), the input power is increased by a factor of 9, but \(\overline{F}\) will be unchanged, so

\[
\overline{F} = \left( \frac{V_{\text{in}}}{2} \right)^2 \left( \frac{0.77 \times 10^{14}}{9} \right) \quad \text{at the i-f output.}
\]

If small signal operation of the final detector is assumed, the sideband signals corresponding to modulation add coherently, so that for 30-percent modulation the detected signal amplitude is 0.3 times the carrier amplitude, and the sideband power is 0.09 times the carrier power. Thus another increase, by the ratio 1/0.09, would be necessary in the input signal power to maintain a given value of \(\overline{F}\), if the noise figure is measured after the final detector. The necessary increase will be reduced, however, by the ratio of audio bandwidth to i-f bandwidth. This ratio is about 2600/65,000, or 25, in the R-36/GR receiver. The relationship between receiver noise figure and receiver sensitivity is then

\[
\overline{F} = \left( \frac{V_{\text{in}}}{3} \right)^2 \left( \frac{0.77 \times 10^{14}}{9} \right) \left( \frac{25}{1} \right) \left( \frac{1}{0.09} \right),
\]

where

\[
V_{\text{in}} = \text{input carrier voltage},
\]

\[
\frac{S+N}{N} = 10 \text{ at the audio output, and}
\]

Modulation = 30 percent (single tone).
As an example, the noise figure corresponding to a measured sensitivity of 0.65-microvolt, 30-percent, 1000-cps modulated input signal, for a ratio of \((S+N)/N = 10\) at the audio output is

\[
\bar{F} = (0.65)^2 \times (10^{-12}) \times (1.93 \times 10^{13}) , \tag{8.8}
\]

\[
= 8.2 ,
\]

\[
\cong 9.1 \text{ db} .
\]

The measurement on which the noise figure in Equation 8.8 was based was an independent sensitivity measurement performed at 300 mc on the R-361/GR receiver, and is within a one-decibel agreement with the value given in Table 8.1.

C. Results of Applying Interference Reduction Techniques

1. Test Results

The schematics of the four experimental chassis tested are shown in Figures 12.48, 12.49, 12.50, and 12.51, in the appendix. The first two of these chassis were tested for third-order intermodulation rejection of the r-f amplifiers alone, excluding the mixer. The results of the tests are in Table 8.2.

<table>
<thead>
<tr>
<th>Amplifier Type</th>
<th>1-Mc Separation (Db)</th>
<th>2-Mc Separation (Db)</th>
<th>5-Mc Separation (Db)</th>
<th>Gain (Db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHFA-B1</td>
<td>68</td>
<td>82</td>
<td>100</td>
<td>19</td>
</tr>
<tr>
<td>UHFA-F1</td>
<td>68</td>
<td>89</td>
<td>115</td>
<td>11.5</td>
</tr>
<tr>
<td>R361/GR</td>
<td>35</td>
<td>38</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

*Tested with 100-millivolt interfering signals.
Each of the four experimental chassis was then mounted as an "outboard" unit on the R-361/GR receiver, and measurements were made of the maximum third-order intermodulation rejection capabilities of the modified receiver. Noise figure was also measured, with the r-f bias voltages set for maximum intermodulation rejection. Third-order intermodulation and noise figure measurements were also made on the receiver with its original r-f chassis, both with and without the 13-mc crystal filter replacing the 40-mc network, and with both fixed grid bias and cathode bias. Table 8.3 lists the test results, along with pertinent data on the experimental chassis.

### TABLE 8.3

R-361/GR RECEIVER PERFORMANCE CHARACTERISTICS

<table>
<thead>
<tr>
<th>R-F Chassis Used</th>
<th>Interfering Signal Amplitudes (Mv)</th>
<th>Third-Order Intermodulation Rejection (Db)</th>
<th>Receiver Noise Figure (Db)</th>
<th>Bias Conditions on Amplifiers</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original receiver</td>
<td>100</td>
<td>40</td>
<td>49</td>
<td>75</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>55</td>
<td></td>
<td>19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>66</td>
<td></td>
<td>19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>62</td>
<td></td>
<td>19</td>
<td></td>
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<tr>
<td></td>
<td>100</td>
<td>37</td>
<td>38</td>
<td>63</td>
<td>10</td>
</tr>
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<td>50</td>
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<tr>
<td></td>
<td>10</td>
<td>47</td>
<td></td>
<td></td>
<td>10</td>
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</tbody>
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### TABLE 8.3 (Continued)

**R-361/GR RECEIVER PERFORMANCE CHARACTERISTICS**

<table>
<thead>
<tr>
<th>R-F Chassis Used</th>
<th>Interfering Signal Amplitudes</th>
<th>Third-Order Intermodulation Rejection (Mc)</th>
<th>Receiver Noise Figure</th>
<th>Bias Conditions on Amplifiers</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Mv)</td>
<td>1 Mc 2 Mc 5 Mc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UHFA-MDI</td>
<td>100</td>
<td>40  65  95</td>
<td>Grid: ( V_1 = V_2 = V_3 = 1.4 )volts</td>
<td></td>
<td>Chassis same as original except for input network</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>68  68  68</td>
<td>Grid: ( V_1 = 1.4 )volts ( V_2 = 2.9 )volts ( V_3 = 2.8 )volts</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>82  82  82</td>
<td>Grid: ( V_1 = 3.0 )volts ( V_2 = 3.4 )volts ( V_3 = 2.2 )volts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UHFA-B2</td>
<td>100</td>
<td>20  20  20</td>
<td>1000-ohm cathode resistors</td>
<td></td>
<td>5876 Tubes</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>40  40  40</td>
<td>1000-ohm cathode resistors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>52  52  52</td>
<td>100-ohm cathode resistors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>71  71  71</td>
<td>100-ohm cathode resistors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UHFA-M1</td>
<td>100</td>
<td>57  57  57</td>
<td>90,000 Grid: ( V_1 = 2.5 )volts ( V_2 = 3.2 )volts ( V_3 = 1.5 )volts ( V_4 \text{ (mixer) } = 2.0 )volts</td>
<td>Amplifiers 6BC4, 6AJ4's mixer 6AJ4</td>
<td></td>
</tr>
<tr>
<td>UHFA-F1</td>
<td>100</td>
<td>69  76  100</td>
<td>200 Cathode bias set for minimum IM</td>
<td>Regular 1-f 40-mc cans amplifiers 2-6AJ4's mixer 6AK5</td>
<td></td>
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<tr>
<td></td>
<td>100</td>
<td>88  82  100</td>
<td>280 Cathode bias set for Minimum IM</td>
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</table>

In Figure 8.5 the third-order intermodulation rejection capabilities of the R-361/GR receiver are plotted versus frequency separation or channel spacing of the two interference producing signals. Curve 1 in Figure 8.5 is for the...
THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS OF A R361/GR RECEIVER MODIFICATIONS:

1. UNMODIFIED RECEIVER
2. FIXED GRID BIAS ON RF AMPLIFIER TUBES: 1.4V
3. FIXED GRID BIAS: 1.4V; INPUT SELECTIVE NETWORK OF FIGURE 8.1
4. EXPERIMENTAL CHASSIS UHFA-F1 REPLACED RECEIVER RF CHASSIS CATHODE BIAS FOR MINIMUM INTERMODULATION 2-6AJ4 AMPLIFIERS 6AK5 MIXER. INPUT SELECTIVE NETWORK OF FIGURE 8.1
5. UNMODIFIED RECEIVER WITH COLLINS PRESELECTOR

INTERFERING SIGNAL AMPLITUDES: 100 mv

Figure 8.5. Third-Order Intermodulation Rejection Characteristics of a R-361A/GR Receiver.
unmodified receiver, i.e., with cathode bias and AVC connected into the r-f amplifier. Curve 2 is for the receiver modified for fixed grid bias of the r-f stages, with the 6J4 and the 6AK5 amplifier cathodes grounded. Curve 3 is for the experimental chassis UHFA-MD1 replacing the receiver r-f chassis. The UHFA-MD1 differed from the receiver r-f chassis in two respects: the experimental unit had the input selective circuit of Figure 8.1 and it also had fixed grid bias.

Curve 4 of Figure 8.5 shows the receiver rejection capabilities with the experimental unit UHFA-Fl replacing the receiver r-f chassis.

Curve 5 of Figure 8.5 shows the rejection capabilities of the receiver with the Collins 156C-2 coaxial preselector.

A test of intermodulation rejection versus interference signal level was made, both with and without the ferrite attenuator as an AVC element ahead of the receiver. The result of the test is shown in Figure 8.6.

Figures 8.7 and 8.8 show the third-order intermodulation rejection characteristics of the receiver (1) unmodified, (2) with a crystal filter replacing the receiver 40-mc network, (3) with fixed cathode bias (no AVC) on the r-f stages, and (4) with the Collins 156C2 coaxial preselector.

2. Discussion of the Test Results

a. Intermodulation Rejection Improvements. The curves of Figure 8.5 show the improvements that can be made in the third-order intermodulations rejection capabilities of the R-361/GR receiver. The improvement represented by the difference between Curve 1 and Curve 2 can be attributed to operation of the r-f amplifiers at a fixed grid bias of 1.4 volts. This bias value was selected not for maximum intermodulation rejection, but for a combination of low intermodulation and low noise figure. Table 8.3 values indicate that with
Figure 8.6. Intermodulation Rejection of the R-361A/GR Receiver with an AVC Operated Ferrite Attenuator Ahead of the Receiver.

higher bias voltages some further improvement in intermodulation rejection could have been realized, but at the expense of increased noise figure.

The further improvement in intermodulation rejection represented by the difference between Curve 2 and Curve 3 of Figure 8.5 can be attributed to the input selective circuit shown in Figure 8.1. Reference to Table 8.3 shows that the improvement in intermodulation is achieved at the price of an increase of the noise figure from 10 to 19. The increase in the noise figure was caused by an insertion loss of about 3 db in the selective network.

The improvement in rejection capabilities represented by Curve 4 of Figure 8.5 can be attributed to (1) the lower gain of the UHFA-Fl experimental
Figure 8.7. Third-Order Intermodulation Rejection Characteristics of an Unmodified GRR-7 Receiver.
Figure 8.8. Third-Order Intermodulation Rejection Characteristics of a GRR-7 Receiver with a 13-mc Crystal Bandpass Filter.
chassis, (2) the use of two instead of three r-f amplifier tubes, (3) fixed bias set for maximum intermodulation rejection, and (4) the use of 6AJ4 tubes instead of 6J4's and a 6AK5. The high noise figure shown in Table 8.3 raises a serious question about the real value of the improved intermodulation rejection caused by the UHFA-F1 unit. The discussion of noise figure measurements below will suggest that the high noise figure was caused by the inherently high noise of the first mixer, and by the fact that the power gain of the UHFA-F1 r-f amplifier was approximately unity.

Curve 5 of Figure 8.5 shows the effect of the Collins coaxial preselector in improving the intermodulation rejection characteristics of the R-361/GR receiver. The usefulness of the straightforward approach — preselection — is apparent. Of course, the disadvantage of the coaxial cavity is in its large size and weight.

Figure 8.6 shows third-order intermodulation rejection of the receiver for the two interfering signals spaced 1 and 2 mc, respectively, above the receiver center frequency. The rejection was measured first with and then without the ferrite attenuator as an AVC element ahead of the receiver. Tests were made with the input signal at several levels, from 0.01 to 0.1 volt. Some improvement from the attenuator is seen, but it is not significant. The crystal filter which replaced the 40-mc network was expected to reduce the overall intermodulation by eliminating interference produced in the second mixer and/or the first few i-f stages. In Figure 8.9 is a comparison of the response characteristics of the crystal filter and the 40-mc network. It can easily be seen that signals at 100 and 200 kc from the center frequency would pass through the 40-mc network and produce third-order interference in the second mixer. Unfortunately, the frequency instability of the test generators did not permit a test with signals so
close to the center frequency. The results shown in Figure 8.7 and 8.8 were of tests with 0.25 mc or greater interfering signal spacings. The curves do show a trend of improvement caused by substitution of the 13-mc crystal filter for the 40-mc network, and it is believed more significant results would be revealed by more refined tests.

The Collins 156C2 preselector produced a striking improvement in the intermodulation rejection of the receiver. The advantage of the straightforward approach of preselectivity is demonstrated.

The curvature of the characteristics for 0.05 mc and 1.0 mc interfering signal separation shown in Figures 8.6, 8.7, and 8.8 demanded explanation. A review was made of the measurements technique and it was found that there was an implicit assumption that the gain of the receiver, which was used as an amplifier to indicate signal levels, did not change when the interference producing signals were switched off. However, the gain characteristics of the r-f amplifier, given in Figure 8.10, showed that an increase in gain of the order of 13 db occurred in the r-f amplifier alone when the 0.1-volt interfering signals were cut off. The on-channel signal required to reproduce the AVC voltage previously caused by the intermodulation signal was thus at least 13 db lower than it would have been if gain had remained constant. The intermodulation rejection measurements made with the technique described above were too large by at least 13 db when the interference producing signals were 0.1 volt. This error, resulting in overly large rejection values for 0.1-volt interference signals is in much of the UHF data reported in this Chapter, and it is not possible to make accurate corrections. It should be noted, however, that the improvements in rejection, where reported, are probably on the low side because of this error.
Figure 8.9. Response of GRR-7 Receiver at Grid of Second Mixer, with and without Crystal Filter.

Figure 8.10. Gain Characteristic of R-F Amplifier in R-361A/GR Receiver.
b. Noise Figure Measurements. The large noise figures shown in Table 8.3 raise a question about the usefulness of the optimum bias technique for reducing intermodulation. It was noted that the optimum rejection bias voltages in the UHFA-MDL chassis were greater than the cathode bias voltages in the receiver r-f unit, and the gain of the experimental unit was therefore less than the receiver unit. This suggested that the noise figures were large because the first mixer noise was high. Further analysis and measurements confirmed this.

The overall noise figure of a receiver and its antenna can be separated so that the contributions of the various components are apparent. Thus

\[ F = F_a + K(F_1 - 1) + \frac{K(F_2 - 1)}{G_1} + \frac{K(F_3 - 1)}{G_1 G_2}, \quad (8.9) \]

where

- \( F \) = overall receiver-plus-antenna noise figure,
- \( F_a \) = antenna noise figure,
- \( K \) = power attenuation from the antenna to the receiver input,
- \( F_1 \) = noise figure of the input section of the receiver, e.g., the r-f amplifier section,
- \( G_1 \) = power gain of the input section,
- \( F_2 \) = noise figure of the second section of the receiver, e.g., the mixer stages,
- \( G_2 \) = power gain of the second section, e.g., the mixer conversion power gain, and
- \( F_3 \) = noise figure of the remainder of the receiver, or to the point of measurement of \( F \).
Equation 8.9, in context with Equations 4.12 and 4.24, indicates the importance of a low noise figure in the mixer as well as in the r-f amplifier stages. To keep intermodulation production low in the later stages of the r-f amplifier, Equations 4.12 and 4.24 point out the desirability for low voltage gain in the r-f section of the receiver, so that the magnitudes of signals giving rise to intermodulation, $E_1$ and $E_2$, will be kept small. Equation 8.9, on the other hand, indicates that the power gain of the r-f section must be high enough to reduce the contribution the mixer adds to the overall noise figure. The power gain of the input section is related to its voltage gain by

$$G_1 = (A_1)^2 \frac{R_1}{R_2}$$

(8.10)

where

$A_1$ = voltage gain of first section,

$R_1$ = resistive component of input impedance of first section,

and

$R_2$ = resistive component of input impedance of second section.

Overall requirements of high receiver sensitivity and low intermodulation production require, in addition to low attenuation between the antenna and the receiver:

1. low noise r-f amplifier stages,

2. low noise mixer stages and i-f amplifier,

3. low voltage gain r-f amplifier stages,

4. high resistive r-f amplifier input impedance,

5. low resistive impedance at the input to the first mixer, and

6. high power gain in the r-f amplifier.
Measurements on the R-361/GR receiver showed

1. the r-f amplifier had a noise figure of about 4,
2. the noise figure of the receiver, with the signal introduced at the first mixer was about 300,
3. the voltage gain of the r-f amplifier was about 1.4,
4. the nominal input impedance of the receiver is 50 ohms,
5. the mixer input impedance was about 200 ohms, and
6. power gain in the r-f amplifier was about 50.

From the measurements it appears that the contribution to the overall noise figure of the mixers and the rest of the receiver is about 300/50, or 6.

Recent developments in mixer circuits indicate that the noise figure obtainable with a 417A, a 6299, or a 416B vacuum tube used as a mixer would be lower by a factor of 5 or 10 than the 6AK5 tube, which is used as a mixer in the R-361/GR receiver.

In contrast to the noise and gain as found in the R-361/GR receiver, consider the following hypothetical receiver:

1. a three-stage r-f amplifier with 50-ohm input and output impedances,
2. a gain of 2.5 in the first stage; gains of 1.0 in the other two stages,
3. noise figures of 3 for each tube,
4. the noise figure of the r-f amplifier would be $3 + \frac{3-1}{6.25} + \frac{3-1}{6.25} = 3.6$,
5. power gain would be 6.25,
6. if the noise figure of the mixers and the rest of the receiver were 40, the contribution to the overall noise figure would be 6.4 for an overall noise figure of 10; the improvement in the noise figure of the receiver measured at the input to the mixer would be $7\frac{1}{2}$, and
7. assuming improved intermodulation rejection would result only from the decreased r-f amplifier voltage gain, the improvement in rejection would be $(5.6)^3$ or 175.
D. Conclusions and Recommendations

1. General Conclusions

The most straightforward way of reducing intermodulation interference in a receiver is by preselection - - frequency selectivity ahead of the r-f amplifier. The Collins 156C-2 coaxial filter accomplishes this, but it is large and heavy. The selective input circuit shown in Figure 8.1 improved the rejection capabilities of the receiver for 2-mc channel spacing about 30-db. The input circuit required only about 2 cubic inches, and could easily be mounted beside the input tube of the R-361/GR receiver r-f amplifier. Insertion loss of the circuit was 3 db, but this could probably be reduced.

The techniques of reducing intermodulation by setting the grid bias of the r-f tubes to a fixed voltage proved satisfactory. Improvement in the R-361/GR was 22 db at 2-mc channel spacing and 40 db at 3-mc spacing when the bias voltages of the r-f amplifiers were set at 1.4 volts, and the cathodes were grounded. This bias voltage gave a receiver noise figure of 10, but was not the optimum value for maximum rejection. Intermodulation rejection improvements for the receiver, for one-megacycle channel spacings and for bias voltages set for maximum rejection, varied from 22 db at a noise figure of 19 (with the R-361/GR amplifier) to 47 db at a noise figure of 1300 (with the UHFA-MDI unit).

The ferrite attenuator improved rejection, but not enough to warrant its use. The power required for its operation necessitates a separate power supply that would add considerable weight and bulk to a receiver installation.

The usefulness of the crystal filter ahead of the i-f amplifier in reducing intermodulation was not proved or disproved by the tests. It will certainly reduce distortion caused by signals which are closer spaced than 0.5-mc to the receiver center frequency, but the frequency stability of the equipment used for
testing was not good enough to prove this conclusively. The crystal filter was recommended for the elimination of interference caused by signals which the 40-mc filter of the present receiver does not remove. The crystal filter would be most useful, however, in a receiver with one mixer and a 13-mc i-f amplifier; and it is not recommended as an actual replacement in the two-mixer, R-361/GR receiver.

The noise figure at the first mixer in the R-361/GR was found to be 300. This is considered excessive. The high mixer noise requires a high power gain in the r-f amplifier, and therefore a high voltage gain -- particularly since the mixer input impedance is higher than the receiver input impedance. The high voltage gain (23 db) in the R-361/GR rendered the receiver rather unsuited to the application of intermodulation reduction techniques such as bias voltages fixed for maximum rejection.

An r-f amplifier-mixer assembly, if it is to have both low noise figure and low intermodulation should have

1. as much input selectivity as possible,
2. low voltage gain,
3. a low ratio of mixer input impedance to receiver input impedance,
4. low noise r-f amplifiers,
5. a low noise mixer,
6. only enough power gain in the r-f amplifiers to render the mixer noise figure contribution acceptably small, and
7. as much as possible of this power gain in the first r-f stage.

The role of the r-f amplifiers should chiefly be to serve as isolation between selective circuits; only secondarily should they serve to reduce the noise contribution of the mixer.
2. Recommendations

a. Modifications of the R-361/GR Receiver. The following modifications are recommended for the R-361/GR receiver:

1. An input selective network, similar to that shown in Figure 8.1, should be developed. The insertion loss should be one decibel or less. The purpose of the network is to achieve as much selectivity as possible ahead of the r-f amplifier.

2. The r-f stages should be operated with grid bias fixed at 1.5 to 1.8 volts on the 6J4 tubes, and 2.2 to 2.5 volts on the 6AK5 amplifier. AVC should be removed from the r-f amplifiers.

b. Design Basis for an Improved Receiver. The following is recommended as a guide in the design of a receiver for high sensitivity and high intermodulation rejection capabilities:

1. An input selective network similar to Figure 8.1.

2. The use of low noise, low intermodulation, r-f amplifier tubes.

3. Fixed bias operation of the r-f stages, without AVC. Large grid-base tubes would probably be required.

4. The development of interstage networks with improved selectivity, possibly similar to the network in Figure 8.1. The primary object of the r-f amplifier selectivity should be to suppress image response of the mixer, and the number of r-f amplifiers used should be no more than are needed to accomplish this.

5. The development of a low noise mixer. An investigation of the practicability of using a refrigerated crystal is suggested.

6. The proper scheduling of r-f stage power gains, with a possible compromise between low noise figure and low intermodulation. Voltage gain should be kept as low as possible.
7. The use of single conversion, and a crystal filter immediately after the mixer, so that no intermodulation from adjacent and alternate channel signals can occur in the i-f amplifiers.
IX. OVERALL CONCLUSIONS AND RECOMMENDATIONS

A. Broad Perspective of Results

Several factors appeared in the course of the various phases of investigation that were significant and are brought together here in a cohesive picture. In the course of instrumentation procedures on the various interference reduction techniques it was obvious that selectivity played an important role in minimizing intermodulation in testing equipment. This implies that, although not a primary pursuit in this contract, the item of preselection of signals ahead of the nonlinear elements of a receiver must be considered the most effective and the most practical present solution to the cross-modulation and intermodulation interference problem.

Intermodulation measurements on amplifiers and mixers lead to the conclusion that (1) fixed bias operation of either circuit yields an improvement in their intermodulation rejection characteristic over the condition where AVC is applied, (2) that a bias point of maximum intermodulation rejection can be found in nearly all types when operated at recommended plate and heater potentials, and (3) there is a need for design and development of tubes possessing either a truly linear or truly square-law transfer characteristic.

The investigation of plate mixer performance showed that when its parameters were scaled to compare with conventional mixer performance no advantage was found in either intermodulation rejection, or conversion gain. This circuit appears attractive only where high level signals are concerned but not in low level receivers where low noise figures are essential.

Application of each of the various interference reducing techniques revealed that (1) preselection provided the greatest single contribution of improvement in intermodulation reduction, (2) fixed bias operation provided
noticeable improvement over AVC condition, and (3) the linear pre-input attenuation provided only a small amount of improvement in comparison to AVC condition.

Thirteen tube types were measured for their third-, fifth-, and seventh-order intermodulation characteristics at low frequencies and nine types were measured at high frequencies. Fifth- and seventh-order intermodulation were found to be negligible compared to third order. Type 6386 demonstrated the effectiveness of tubes designed with nearly square-law transfer characteristics. UHF measurements showed three types to be much better for intermodulation rejection than the 6J4, currently used in the R-361A/GR receiver. These types were the 5876, 6AJ4 and 6BC4.

Analytic techniques to evaluate tube parameters mathematically were investigated. A program containing the various mathematical steps was developed that utilizes the IBM-650 magnetic-drum computer. Data obtained on several tubes demonstrate that it is possible with these methods to obtain, as a function of bias, the third-order coefficient of the Taylor's series which represents the transfer characteristic. This parameter is important in the study of the intermodulation characteristics of amplifier tubes. In connection with the study of intermodulation characteristics of mixers sufficient data was available from results to make a qualitative evaluation of the fourth-order term.

Investigation of ferrite materials led to the construction of a linear UHF attenuator that could be used as an AVC in receiving equipment. Application of this method is limited by the size of the equipment and by the power requirement. Response time of the system constructed was found to be slow compared to the AVC system of the R-361A/GR.

B. Recommendations

Evaluation of the results of investigation of the various interference reducing techniques in this report reveal that certain recommendations are in
order for further study and development:

1. Investigation of the feasibility of designing tubes with square-law transfer function.

2. Investigation of recently developed crystal mixers for the UHF region to determine their noise figures and their interference rejection properties.

3. Investigation of better approximating functions to provide a truer representation of the transfer characteristics of tubes so that higher order coefficients may be obtained more reliably.

4. More attention to the development of small sized highly selective UHF networks that would be acceptable for employment in current receiver units.

5. Investigation of a proposed realizable design basis for an improved UHF receiver possessing good intermodulation rejection properties and high sensitivity. The design specifications of this receiver are:

   (a) use of a highly selective input network (tunable),

   (b) low noise, low intermodulation r-f amplifier tubes for first stage,

   (c) large grid-base, low noise r-f amplifier tubes for succeeding stages,

   (d) improved interstage selectivity and shielding for good image rejection,

   (e) high gain in the first r-f stage, low gain in the succeeding stages,

   (f) employment of recently developed low noise crystal diode mixers, and

   (g) use of single conversion with a currently available highly selective crystal i-f filter following the first mixer.
X. KEY TECHNICAL PERSONNEL

The following personnel have contributed to the performance and results of this investigation:

**Engineering Personnel**

B. L. Blanks, Research Assistant

W. R. Free, Assistant Research Engineer

R. E. Meek, Research Engineer (Project Director)

H. L. McKinley, Research Associate

R. R. Propp, Research Assistant

S. L. Robinette, Research Engineer

W. B. Warren, Assistant Research Engineer

**Technician Personnel**

H. M. Bivens, Graduate Assistant

R. L. Finlay, Student Assistant

R. E. Poupard, Graduate Assistant

W. L. Reagh, Electronic Technician

The following paragraphs include a brief resume of the qualifications and length of service on the project of each of the engineering personnel listed above:

Mr. Blanks joined the project 1 February 1957 and served on a full time basis. He holds a B.S. degree in Physics from Emory University and has done graduate work in the same field. His previous professional experience includes 3 years as transmitter technician and 8 years as transmitter engineer for two local broadcast stations. He holds an advanced class radio amateur's license.

Mr. Free joined the project 15 June 1957 serving on a full time basis. He holds a B.S. degree in Electrical Engineering from Georgia Tech and is
currently purusing graduate work toward a M.S. degree in the same field. His previous professional experience includes three years as Development Engineer for Sperry Gyroscope Company and one year in crystal oscillator development on another project at Georgia Tech. He served three years as an Electronic Technician in the U. S. Coast Guard.

Mr. Meek was appointed director of the project at its inception 1 December 1956 and served in this capacity on a full time basis. He holds a B.S. degree in Electrical Engineering from the University of Kentucky and has done graduate work in the same field. His previous professional experience includes four years in armed services as radar and electronics instructor, two years as instructor in Electrical Engineering at the University of Kentucky, and seven years as research engineer in electronics at Georgia Tech.

Mr. McKinley became associated with the project 1 December 1956 and has served on a quarter time basis. He holds the degrees of Electrical Engineer and M.S. in E.E. and is licensed by the State of Georgia as a professional Electrical Engineer. His previous experience includes a number of years in industrial power and lighting with the Georgia Power Company, fourteen years of teaching communication and electronics at Georgia Tech, and several years association with various research and development activities at the Engineering Experiment Station.

Mr. Propp joined the project on a full time basis 15 March 1957. He holds a B.S. degree in Electrical Engineering from Georgia Tech and is currently pur-奢着 graduate work toward a M.S. degree in the same field. His previous experience was primarily in the field of commercial merchandising and cost accounting.
Mr. Robinette became a member of the project 1 December 1956 and served on a full time basis. He holds a B.S. degree in Electrical Engineering from the University of Alabama and has done graduate work toward a M.S. degree in the same field at Georgia Tech. His previous professional experience includes two years in electronic instrumentation with Rohm and Haas Company, two years with Southern Research Institute in similar work, and two years in electronic research and development at Georgia Tech.

Mr. Warren served the project on a full time basis from 1 December 1956 to 1 February 1957. He holds an M.S. degree in Electrical Engineering from Georgia Tech. His previous experience includes three years as electronics technician in the U. S. Navy and two years research and development in electronics on other projects at Georgia Tech.

Respectfully submitted:

R. E. Meek
Project Director

Approved:

J. E. Boyd, Director
Engineering Experiment Station
XI. BIBLIOGRAPHY

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XII. APPENDIX

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A. Outline of Tube-Evaluation Computer Programs for Analog and Digital Computers

1. Analog Computer

For study of vacuum tube characteristics the problem on the analog computer is that of producing dynamic plots of the transfer characteristic and its first three time derivatives for a group of triodes.

Preliminary programming efforts presented the fact that an accurate third successive differentiation is unattainable with the Ease computer, even with special differentiating circuits. The problem was revised to obtain only the transfer characteristic and its first two derivatives.

The program consists of applying a linearly decreasing negative voltage from the computer to the grid of the test triode which is incorporated in a special amplifier circuit (Figure 12.1). The output across the plate load resistor of the triode amplifier is returned to the computer where it is amplified and plotted as a transfer characteristic. The amplified signal is also applied to a chain of special differentiator circuits which produce the first and second derivatives. The derivatives are then plotted one at a time.

The scale factor of the transfer characteristic is 20 while those of the derivatives are dependent upon the speed of plotting or the rate of voltage change at the tube grid. The differentiators themselves have a scale factor of unity.

The differentiator is inherently a noisy computer component and must be altered to obtain favorable results. A differentiator was devised using a second order loop connected in such a way that it is analogous to a perfect differentiator followed by a low pass LC filter. This arrangement removed the higher frequencies of noise and produced very little phase shift with an $\omega$ of one. The sweep was run slowly enough such that little error was involved.
Figure 12.1. Analog Computer Flow Diagram for Tube Evaluation.
It was found that still more noise could be removed by differentiating twice and integrating once for each derivative (Figure 12.2). This is the same in effect as using two LC low pass filters behind each perfect differentiator.

The amplitude errors of the program should be within $\pm 1$ percent. The phase errors will be somewhat greater due to the double filtering on the differentiators. The phase error is about two degrees per differentiator or a total of 8 degrees for the second derivative at an $\omega$ of one. The overall error should not be greater than 5 percent.

2. Digital Computer Program for the Evaluation of Vacuum Tube Non-linearities

The following program computes from transfer curve data: (1) a seventh degree Tshebysheff-Polynomial approximation to the transfer curve using the "Gram-Tshebysheff Worksheet", (2) the approximating polynomial at fifty values of bias, (3) residues at the fifteen input data points, and (4) $C_N(C_1$ or $C_2$ or $C_3$) at forty bias values. This program is written in the Bell General Purpose System Language for the IBM 650.

ORDERS

1 - 5           OUTLINE OF PROGRAM
Start the Program and call in new data.

6 - 39         Evaluation of $a_1 = \frac{1}{D_1} \sum N_1(x) \phi(x)$ of step two of polynomial worksheet.

40 - 61        Evaluation b's from worksheet and print out as coefficient of polynomial. Print out of input data.

62 - 82        Evaluation of Tshebysheff Polynomial at 50 points by formulas

83 - 94        Calculation of residues between Tshebysheff Polynomial and experimental points.

95 - 126       Calculation of Espley method for $C_1$, $C_2$ or $C_3$ at 40 different bias points.

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Figure 12.2. Functional Diagram of Analog Computer System for Investigation of Tube Characteristic.
Table 12.1

Gramm-Tchebyshev Worksheet

Step 1. Divide the interval of the independent variable into 14 equal parts and find the corresponding values of the dependent variable. These values are listed as $\phi(X)$. The transformed interval is $0 \leq X \leq 1$.

Step 2. $a_1 = \frac{1}{D_1} \sum N_1(X) \phi(X)$

$$a_2 = \frac{\sum N_2(X)\phi(X)}{D_2}$$

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<thead>
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<th>X</th>
<th>$N_0(X)$</th>
<th>$N_1(X)$</th>
<th>$N_2(X)$</th>
<th>$N_3(X)$</th>
<th>$N_4(X)$</th>
<th>$N_5(X)$</th>
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<th>$N_7(X)$</th>
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</table>
TABLE 12.1 (Continued)

GRAM-TSHEBYSHEFF WORKSHEET

Step 3. \( \phi^*(x) = b_0 + b_1x + \ldots + b_7x^7 \)

\[
b_2 = \frac{41580 a_2 + 242550 a_3 + \ldots + 25912964 a_7}{6435}
\]

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</table>
# Table 12.2

## Master Program for Vacuum Tube Characteristic Evaluation -- IBM 650 Computer

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<thead>
<tr>
<th>Order No.</th>
<th>Order</th>
<th>Operation</th>
<th>Result of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>+0 800 049 000</td>
<td>Program point No. 49</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>+7 000 190 195</td>
<td>Read in data from 190 to 195, stop if data is not available</td>
<td>14, initial bias, bias increment, bias evaluation increment, program constant</td>
</tr>
<tr>
<td>3.</td>
<td>+7 000 520 534</td>
<td>Read in data from 520 to 534</td>
<td>Points from transfer curve</td>
</tr>
<tr>
<td>4.</td>
<td>+7 000 570 575</td>
<td>Read in data from 570 to 575</td>
<td>Espley constants</td>
</tr>
<tr>
<td>5.</td>
<td>+7 300 190 195</td>
<td>Punch out from 190 to 195</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>+9 800 001 000</td>
<td>Program Point No. 1</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>+9 100 100 000</td>
<td>Modify the next non nine order of form A B C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>X XXX XXX XXX by adding one to A part</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>+2 200 520 000</td>
<td>Multiply number in 200 by number in 520 and store in 000</td>
<td>N(0) (0)</td>
</tr>
<tr>
<td>9.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of next non nine order</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>+4 210 521 000</td>
<td>Multiply No. in 210 by No. in 521 and add previous result store in 000</td>
<td>N(0) (0) + N(1/14) (1/14)</td>
</tr>
<tr>
<td>11.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of next non nine order</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>+4 220 522 000</td>
<td>Multiply No. in 220 by No. in 522 and add previous results store in 000</td>
<td>N(0) (0) + N(1/14) (1/14) + N(2/14) (2/14)</td>
</tr>
<tr>
<td>13.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of next non nine order</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>+4 230 523 000</td>
<td>Multiply number in 230 by number in 523 and add previous result and store 000</td>
<td>N(0) (0) + N(1/14) (1/14) + ... N(3/14) (3/14)</td>
</tr>
<tr>
<td>15.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of next non nine order</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>+4 240 524 000</td>
<td>Multiply number in 240 by number in 524 and add previous result and store 000</td>
<td>N(0) (0) + N(1/14) (1/14) + ... N(4/14) (4/14)</td>
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### TABLE 12.2 (Continued)

**MASTER PROGRAM FOR VACUUM TUBE CHARACTERISTIC EVALUATION -- IBM 650 COMPUTER**

<table>
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<th>Order</th>
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<th>Result of Operation</th>
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<td>17.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of next non nine order</td>
<td>$N_{o}(0) \phi(0) + N_{o}(1/14) \phi(1/14) + \ldots + N_{o}(5/14) \phi(5/14)$</td>
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<tr>
<td>18.</td>
<td>+4 250 525 000</td>
<td>Multiply number in 250 by number in 525 and add previous result and store in 000</td>
<td>$N_{o}(0) \phi(0) + N_{o}(1/14) \phi(1/14) + \ldots + N_{o}(6/14) \phi(6/14)$</td>
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<tr>
<td>19.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of next non nine order</td>
<td>$N_{o}(0) \phi(0) + N_{o}(1/14) \phi(1/14) + \ldots + N_{o}(7/14) \phi(7/14)$</td>
</tr>
<tr>
<td>20.</td>
<td>+4 260 526 000</td>
<td>Multiply number in 260 by number in 526 and add previous result and store in 000</td>
<td>$N_{o}(0) \phi(0) + N_{o}(1/14) \phi(1/14) + \ldots + N_{o}(8/14) \phi(8/14)$</td>
</tr>
<tr>
<td>21.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of the next non nine order</td>
<td>$N_{o}(0) \phi(0) + N_{o}(1/14) \phi(1/14) + \ldots + N_{o}(9/14) \phi(9/14)$</td>
</tr>
<tr>
<td>22.</td>
<td>+4 270 527 000</td>
<td>Multiply number 270 by number in 527 and add previous result and store in 000</td>
<td>$N_{o}(0) \phi(0) + N_{o}(1/14) \phi(1/14) + \ldots + N_{o}(10/14) \phi(10/14)$</td>
</tr>
</tbody>
</table>
TABLE 12.2 (Continued)

**MASTER PROGRAM FOR VACUUM TUBE CHARACTERISTIC EVALUATION -- IBM 650 COMPUTER**

<table>
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<th>Order</th>
<th>Operation</th>
<th>Result of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of next non nine order</td>
<td>N(_o)(0) (\phi)(0) + N(_o)(1/14) (\phi)(1/14) + ... + N(_o)(13/14) (\phi)(13/14)</td>
</tr>
<tr>
<td>30.</td>
<td>+4 310 531 000</td>
<td>Multiply number in 310 by number in 531 and add previous result and store in 000</td>
<td></td>
</tr>
<tr>
<td>31.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of the next non nine order</td>
<td>N(_o)(0) (\phi)(0) + N(_o)(1/14) (\phi)(1/14) + ... + N(_o)(13/14) (\phi)(13/14)</td>
</tr>
<tr>
<td>32.</td>
<td>+4 320 532 000</td>
<td>Multiply number in 320 by number in 532 and add previous results and store 000</td>
<td></td>
</tr>
<tr>
<td>33.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of the next non nine order</td>
<td>N(_o)(0) (\phi)(0) + N(_o)(1/14) (\phi)(1/14) + ... + N(_o)(13/14) (\phi)(13/14)</td>
</tr>
<tr>
<td>34.</td>
<td>+4 330 523 000</td>
<td>Multiply number in 330 by number in 533 and add previous result and store in 000</td>
<td></td>
</tr>
<tr>
<td>35.</td>
<td>+9 100 100 000</td>
<td>Add one to A part of next non nine order</td>
<td>N(_o)(0) (\phi)(0) + N(_o)(1/14) (\phi)(1/14) + ... + N(_o)(13/14) (\phi)(13/14)</td>
</tr>
<tr>
<td>36.</td>
<td>+4 340 534 000</td>
<td>Multiply number in 340 by number in 534 and add previous result in 000</td>
<td></td>
</tr>
<tr>
<td>37.</td>
<td>+9 100 011 000</td>
<td>Add to B &amp; C parts of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>38.</td>
<td>+3 000 390 500</td>
<td>Divide number in 000 by number in 390 and store in 500</td>
<td>a(_i) = (\frac{1}{D_1}) \sum N(_i)(x) (\phi)(x) in 50 i</td>
</tr>
<tr>
<td>39.</td>
<td>+8 101 008 001</td>
<td>Transfer to FP 1 and repeat loop 8 times</td>
<td>9 100 100 000 orders interchange N(_1)'s for N(_o)'s, N(_2)'s for N(_1)'s, ... N(_7)'s for N(_6)'s</td>
</tr>
<tr>
<td>40.</td>
<td>+9 800 002 000</td>
<td>Program Point 2</td>
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<tr>
<td>Order No.</td>
<td>Order</td>
<td>Operation</td>
<td>Result of Operation</td>
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</tr>
<tr>
<td>42.</td>
<td>+2 400 500 000</td>
<td>Multiply number in 400 by number in 500 and store 000</td>
<td>$M_{o}(1) a_o$</td>
</tr>
<tr>
<td>43.</td>
<td>+9 200 100 000</td>
<td>Add 1 to the A part of the next non nine order</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1$</td>
</tr>
<tr>
<td>44.</td>
<td>+4 410 501 000</td>
<td>Multiply number in 410 by number in 501 and add previous result and store in 000</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(3) a_2$</td>
</tr>
<tr>
<td>45.</td>
<td>+9 200 100 000</td>
<td>Add 1 to the A part of the next non nine order</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(4) a_3$</td>
</tr>
<tr>
<td>46.</td>
<td>+4 420 502 000</td>
<td>Multiply number in 420 by number in 502 and add previous result and store in 000</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(5) a_4$</td>
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<tr>
<td>47.</td>
<td>+9 200 100 000</td>
<td>Add 1 to the A part of the next non nine order</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(6) a_5$</td>
</tr>
<tr>
<td>48.</td>
<td>+4 430 503 000</td>
<td>Multiply number in 430 by number in 503 and add previous result and store in 000</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(5) a_4$</td>
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<tr>
<td>49.</td>
<td>+9 200 100 000</td>
<td>Add 1 to the A part of the next non nine order</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(6) a_5$</td>
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<tr>
<td>50.</td>
<td>+4 440 504 000</td>
<td>Multiply number in 440 by number in 504 and add previous result and store in 000</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(6) a_5$</td>
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<td>51.</td>
<td>+9 200 100 000</td>
<td>Add 1 to the A part of the next non nine order</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(6) a_5$</td>
</tr>
<tr>
<td>52.</td>
<td>+4 450 505 000</td>
<td>Multiply number in 450 by number in 505 and add previous result and store in 000</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(6) a_5$</td>
</tr>
<tr>
<td>53.</td>
<td>+9 200 100 000</td>
<td>Add 1 to the A part of the next non nine order</td>
<td>$M_{o}(1) a_o + M_{o}(2) a_1 + \ldots + M_{o}(6) a_5$</td>
</tr>
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</table>
### TABLE 12.2 (Continued)

**MASTER PROGRAM FOR VACUUM TUBE CHARACTERISTIC EVALUATION -- IBM 650 COMPUTER**

<table>
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<th>Order</th>
<th>Operation</th>
<th>Result of Operation</th>
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</thead>
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<tr>
<td>54.</td>
<td>+4 460 506 000</td>
<td>Multiply number in 460 by number in 506 and add previous result and store in 000</td>
<td>$M_0(1)a_0 + M_0(2)a_1 + \ldots + M_0(7)a_6$</td>
</tr>
<tr>
<td>55.</td>
<td>+9 200 100 000</td>
<td>Add one to the A part of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>56.</td>
<td>+4 470 507 000</td>
<td>Multiply number in 470 by number in 507 and add previous result and store in 000</td>
<td>$M_0(1)a_0 + M_0(2)a_1 + \ldots + M_0(8)a_8$</td>
</tr>
<tr>
<td>57.</td>
<td>+9 200 011 000</td>
<td>Add one to the B &amp; C part of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>58.</td>
<td>+3 000 480 510</td>
<td>Divide number in 300 by number in 480 and store in 510</td>
<td>$\frac{1}{M_0} \sum_{N=0}^{8} M(N)a_n$</td>
</tr>
<tr>
<td>59.</td>
<td>+8 201 008 002</td>
<td>Transfer to program point 2 and repeat loop 8 times</td>
<td>Transfer to program point 2 eight times to calculate $b_0$, $b_1$, $b_2$, $\ldots$, $b_7$ by changing $M_0$ to $M_1$, $M_1$ to $M_2$, $\ldots$, $M_6$ to $M_7$</td>
</tr>
<tr>
<td>60.</td>
<td>+7 300 510 518</td>
<td>Punch out numbers in 510 to 518</td>
<td></td>
</tr>
<tr>
<td>61.</td>
<td>+7 300 520 534</td>
<td>Punch out numbers in 520 to 534</td>
<td></td>
</tr>
<tr>
<td>62.</td>
<td>+7 201 510 500</td>
<td>Move number in 500 to 510</td>
<td>Store $b_0$ which is value of polynomial at 0 in 500</td>
</tr>
<tr>
<td>63.</td>
<td>+7 215 520 150</td>
<td>Move number in 520 and next fourteen numbers to 150 and next fourteen addresses</td>
<td></td>
</tr>
<tr>
<td>64.</td>
<td>+7 208 510 170</td>
<td>Move number in 510 and next seven numbers to 170 and next seven addresses</td>
<td></td>
</tr>
</tbody>
</table>

---

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TABLE 12.2 (Continued)

MASTER PROGRAM FOR VACUUM TUBE CHARACTERISTIC EVALUATION -- IBM 650 COMPUTER

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Order</th>
<th>Operation</th>
<th>Result of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.</td>
<td>+3 192 193 182</td>
<td>Divide number in 192 by number in 193 and store in 182</td>
<td>Data increment ( \div ) evaluation increment</td>
</tr>
<tr>
<td>66.</td>
<td>+2 182 190 180</td>
<td>Multiply number in 182 by number in 190 and store in 180</td>
<td>(-\frac{\text{data increment}}{\text{evaluation increment}}) (14)</td>
</tr>
<tr>
<td>67.</td>
<td>+7 300 180 180</td>
<td>Punch out number in 180</td>
<td></td>
</tr>
<tr>
<td>68.</td>
<td>+3 901 180 180</td>
<td>Divide number in 901 by number in 180 and store in 180</td>
<td></td>
</tr>
<tr>
<td>69.</td>
<td>+1 900 180 181</td>
<td>Add number in 900 to number in 180 and store in 181</td>
<td></td>
</tr>
<tr>
<td>70.</td>
<td>+2 182 194 182</td>
<td>Multiply number in 182 by number in 194 and store in 182</td>
<td></td>
</tr>
<tr>
<td>71.</td>
<td>+9 800 020 000</td>
<td>Program Point 20</td>
<td></td>
</tr>
<tr>
<td>72.</td>
<td>+1 180 900 000</td>
<td>Add number in 180 to number in 900 and store in zero</td>
<td>Store 180 also in 181 since 900 has 0</td>
</tr>
<tr>
<td>73.</td>
<td>+5 177 176 000</td>
<td>Multiply number in 177 by previous result and add number in 176 and store in 000</td>
<td></td>
</tr>
<tr>
<td>74.</td>
<td>+5 180 175 000</td>
<td>Multiply number in 180 by previous result and add number in 175 and store in 000</td>
<td></td>
</tr>
<tr>
<td>75.</td>
<td>+5 180 174 000</td>
<td>Multiply number in 180 by previous result and add number in 174 and store in 000</td>
<td></td>
</tr>
<tr>
<td>76.</td>
<td>+5 180 173 000</td>
<td>Multiply number in 180 by previous result and add number in 173 and store in 000</td>
<td></td>
</tr>
<tr>
<td>77.</td>
<td>+5 180 172 000</td>
<td>Multiply number in 180 by previous result and add number in 172 and store in 000</td>
<td></td>
</tr>
</tbody>
</table>

\[
\begin{align*}
(b_7 x + b_6)x + b_5 \\
[(b_7 x + b_6)x + b_5]x + b_4 \\
\left[\left[(b_7 x + b_6)x + b_5\right]x + b_4\right]x + b_3 \\
\left[\left[\left((b_7 x + b_6)x + b_5\right) x + b_4\right]x + b_3\right]x + b_2
\end{align*}
\]
### Table 12.2 (Continued)

**MASTER PROGRAM FOR VACUUM TUBE CHARACTERISTIC EVALUATION -- IBM 650 COMPUTER**

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Order</th>
<th>Operation</th>
<th>Result of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.</td>
<td>+5 180 171 000</td>
<td>Multiply number in 180 by previous result and add number in 171 and store in 000</td>
<td>( \left[ \sum \left( b_7 x + b_6 \right) x + b_5 \right] x + b_4 x + b_3 x + b_2 x + b_1 + b_o )</td>
</tr>
<tr>
<td>79.</td>
<td>+9 100 001 000</td>
<td>Add one to the C part of the next non nine order</td>
<td>Change address of evaluation storage from 501 to 500</td>
</tr>
<tr>
<td>80.</td>
<td>+5 180 170 501</td>
<td>Multiply number in 180 by previous result and add number in 170 and store in 501</td>
<td>( \left[ \sum \left( b_7 x + b_6 \right) x + b_5 \right] x + b_4 x + b_3 x + b_2 x + b_1 ) Change x to 2x to 3x ... 49x</td>
</tr>
<tr>
<td>81.</td>
<td>+1 180 181 180</td>
<td>Add number in 180 to number in 181 and store in 180</td>
<td>Calculate evaluation 50 times</td>
</tr>
<tr>
<td>82.</td>
<td>+8 101 049 020</td>
<td>Transfer to PP 20 and repeat loop 49 times</td>
<td></td>
</tr>
<tr>
<td>83.</td>
<td>+9 800 021 000</td>
<td>P.P. 21</td>
<td></td>
</tr>
<tr>
<td>84.</td>
<td>+9 100 011 000</td>
<td>Add 1 to B and C parts of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>85.</td>
<td>+9 200 100 000</td>
<td>Add 1 to A part of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>86.</td>
<td>-1 500 150 150</td>
<td>Subtract number in 150 from number in 500 and store in 150</td>
<td></td>
</tr>
<tr>
<td>87.</td>
<td>+8 101 015 022</td>
<td>Transfer to program part 22 and repeat loop 15 times</td>
<td></td>
</tr>
<tr>
<td>88.</td>
<td>+8 000 000 023</td>
<td>Transfer to Program Point 23</td>
<td></td>
</tr>
<tr>
<td>89.</td>
<td>+9 800 022 000</td>
<td>Program Point 22</td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 12.2 (Continued)

**MASTER PROGRAM FOR VACUUM TUBE CHARACTERISTIC EVALUATION -- IBM 650 COMPUTER**

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Order</th>
<th>Operation</th>
<th>Result of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.</td>
<td>+0 200 182 000</td>
<td>Add number in 182 to next order</td>
<td>Add ( \text{data increment} ) ( \text{evaluation increment} ) ( (.0001) 10^{-50} ) to next order. Order 90 causes order 91 to become ( 820 \times 0.019 ) ( 0.021 ) where ( x = ) ( \text{data increment} ) ( \text{evaluation increment} ). The ( x ) increment places the right evaluation in order 86 to form the residues by using order 85 to modify 86.</td>
</tr>
<tr>
<td>91.</td>
<td>+8 200 019 021</td>
<td>Transfer the Program Part 21 and repeat loop 19 times</td>
<td></td>
</tr>
<tr>
<td>92.</td>
<td>+9 800 023 000</td>
<td>Program Point 23</td>
<td>Punch out residues</td>
</tr>
<tr>
<td>93.</td>
<td>+9 600 002 000</td>
<td>Reset index register 2</td>
<td>Punch out first five evaluations of polynomial</td>
</tr>
<tr>
<td>94.</td>
<td>+7 300 150 164</td>
<td>Punch out numbers in 150 to 164</td>
<td>( 10/2 = 5 )</td>
</tr>
<tr>
<td>95.</td>
<td>+7 300 500 504</td>
<td>Punch out numbers in 500 to 504</td>
<td>Multiply ( 5 ) times evaluation increment 193</td>
</tr>
<tr>
<td>96.</td>
<td>+3 905 902 649</td>
<td>Divide number in 905 by number in 902 and store in 649</td>
<td>Add initial bias (191) to ( 5 ) times evaluation increment</td>
</tr>
<tr>
<td>97.</td>
<td>+2 649 193 649</td>
<td>Multiply number in 649 by number in 193 and store in 649</td>
<td></td>
</tr>
<tr>
<td>98.</td>
<td>+1 649 191 649</td>
<td>Add number in 649 to number in 191, store in 649</td>
<td></td>
</tr>
<tr>
<td>99.</td>
<td>+9 800 031 000</td>
<td>Program Point 31</td>
<td></td>
</tr>
<tr>
<td>100.</td>
<td>+9 200 110 000</td>
<td>Add one to A and B parts of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>101.</td>
<td>-1 500 510 556</td>
<td>Subtract number in 510 from number in 500, store in 556</td>
<td>( I_{11} - I_{1} )</td>
</tr>
</tbody>
</table>
### Table 12.2 (Continued)

**MASTER PROGRAM FOR VACUUM TUBE CHARACTERISTIC EVALUATION -- IBM 650 COMPUTER**

<table>
<thead>
<tr>
<th>Order No.</th>
<th>Order</th>
<th>Operation</th>
<th>Result of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>102.</td>
<td>+5 570 900 559</td>
<td>Multiply number in 570 by previous results and add number in 900 and store 559</td>
<td>(-820(I_{11} - I_1))</td>
</tr>
<tr>
<td>103.</td>
<td>+9 200 110 000</td>
<td>Add one to A and B parts of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>104.</td>
<td>-1 501 509 558</td>
<td>Subtract number in 509 from number in 501 and store in 558</td>
<td>(I_{10} - I_2)</td>
</tr>
<tr>
<td>105.</td>
<td>+5 571 900 559</td>
<td>Multiply 571 by previous result and add number in 900 and store in 559</td>
<td>(10088(I_{10} - I_2))</td>
</tr>
<tr>
<td>106.</td>
<td>+9 200 110 000</td>
<td>Add one to A and B parts of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>107.</td>
<td>-1 502 508 560</td>
<td>Subtract number in 508 from number in 502 and store in 560</td>
<td>(I_9 - I_3)</td>
</tr>
<tr>
<td>108.</td>
<td>+5 572 900 561</td>
<td>Multiply 572 by previous result and add number in 900 and store in 561</td>
<td>(-58428(I_9 - I_3))</td>
</tr>
<tr>
<td>109.</td>
<td>+9 200 110 000</td>
<td>Add one to A and B parts of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>110.</td>
<td>-1 503 507 562</td>
<td>Subtract number in 507 from number in 503 and store in 562</td>
<td>(I_8 - I_4)</td>
</tr>
<tr>
<td>111.</td>
<td>+5 573 900 563</td>
<td>Multiply number in 573 by previous result and add number in 900 and store in 563</td>
<td>(20971.2(I_8 - I_4))</td>
</tr>
<tr>
<td>112.</td>
<td>+9 200 110 000</td>
<td>Add one to A and B parts of next non nine order</td>
<td></td>
</tr>
<tr>
<td>113.</td>
<td>-1 504 506 564</td>
<td>Subtract number in 506 from number in 504 and store in 564</td>
<td>(I_7 - I_5)</td>
</tr>
<tr>
<td>114.</td>
<td>+5 574 900 565</td>
<td>Multiply number in 574 by previous result and add number in 900 and store 565</td>
<td>(-280392(I_7 - I_5))</td>
</tr>
<tr>
<td>115.</td>
<td>+5 557 559 000</td>
<td>Add number in 579 to number in 559 and store in 000</td>
<td>(-820(I_{11} - I_1) + 10088(I_{10} - I_2))</td>
</tr>
<tr>
<td>Order No.</td>
<td>Order</td>
<td>Operation</td>
<td>Result of Operation</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>-----------</td>
<td>---------------------</td>
</tr>
<tr>
<td>116.</td>
<td>+1 561 000 000</td>
<td>Add number in 561 to number in 000 and store in 000</td>
<td>-820(I_{11} - I_1) + 10088(I_{10} - I_2) - 58428(I_9 - I_3)</td>
</tr>
<tr>
<td>117.</td>
<td>+1 563 000 000</td>
<td>Add number in 563 to number in 000 and store in 000</td>
<td>-820(I_{11} - I_1) + 10088(I_{10} - I_2) - 58428(I_9 - I_3) + 209712(I_8 - I_4)</td>
</tr>
<tr>
<td>118.</td>
<td>+1 565 000 000</td>
<td>Add number in 565 to number in 000 and store in 000</td>
<td>-820(I_{11} - I_1) + 10088(I_{10} - I_2) - 58428(I_9 - I_3) + 209712(I_8 - I_4) - 280392(I_7 - I_5)</td>
</tr>
<tr>
<td>119.</td>
<td>+2 000 575 651</td>
<td>Multiply number in 000 by number in 575 and store in 651</td>
<td>Multiply previous result by 575 and store in 651 which equals ( \frac{1}{725760(AE_8)^3} ) (note that this value in 575 must be given to the machine and will vary with evaluation increment)</td>
</tr>
<tr>
<td>120.</td>
<td>+9 200 010 000</td>
<td>Add one to B part of the next non nine order</td>
<td></td>
</tr>
<tr>
<td>121.</td>
<td>+7 201 505 650</td>
<td>Move number in 505 to address 650</td>
<td>Move value of I_6 to 650</td>
</tr>
<tr>
<td>122.</td>
<td>+7 300 649 651</td>
<td>Punch out numbers in 649 to 651</td>
<td>Punch out bias, current, C_3</td>
</tr>
<tr>
<td>123.</td>
<td>+1 649 193 649</td>
<td>Add number in 649 to number in 193 and store in 649</td>
<td>Add bias evaluation increment to last bias for evaluation of C_3</td>
</tr>
<tr>
<td>124.</td>
<td>+8 201 040 031</td>
<td>Transfer to Program point 31 and repeat loop 40 times</td>
<td>Find C_3 for 40 values of bias</td>
</tr>
<tr>
<td>Order No.</td>
<td>Order</td>
<td>Operation</td>
<td>Result of Operation</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>----------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>125.</td>
<td>+7 300 545 549</td>
<td>Punch out numbers from 545 to 549</td>
<td>Punch out last five current evaluations from Tshebysheff Polynomial</td>
</tr>
<tr>
<td>126.</td>
<td>+8 000 000 049</td>
<td>Transfer to Program Point 49</td>
<td>Return to program point 49 and program will continue if more data is available at readin unit.</td>
</tr>
</tbody>
</table>
XII. APPENDIX

B. Intermodulation Characteristics of Several Amplifier and Mixer Tubes
Figure 12.3. Composite Characteristics of Distortion Coefficients and Intermodulation Rejection for 6AJ4.
Figure 12.4. Composite Characteristics of Distortion Coefficients and Intermodulation Rejection for 6BC4.
Figure 12.5. Composite Characteristics of Distortion Coefficients and Intermodulation Rejection for 6BQ7.
Figure 12.6. Composite Characteristics of Distortion Coefficients and Intermodulation Rejection for 6AN4.
Figure 12.7. Composite Characteristics of Distortion Coefficients and Intermodulation Rejection for 6J4.
Figure 12.8. Composite Characteristics of Distortion Coefficients and Intermodulation Rejection for 417A.
Figure 12.9. Composite Characteristics of Distortion Coefficients and Intermodulation Rejection for 6386.
Figure 12.10. 6AF4 Low Frequency Third-Order Intermodulation Characteristics.
LOW FREQUENCY INTERMODULATION REJECTION CHARACTERISTICS FIVE 6AJ4 TUBES

- $E_b = 125\text{ V}$
- $E_f = 6.4\text{ V}$
- $F_{IM} = 27\text{ KC}$

Figure 12.11. 6AJ4 Low Frequency Third-Order Intermodulation Characteristics.
Figure 12.12. 6AM4 Low Frequency Third-Order Intermodulation Characteristics.
Figure 12.13. 6AN4 Low Frequency Third-Order Intermodulation Characteristics.
GRID BIAS - volts

THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTIC FOR FIVE TYPE 6BC4

Figure 12.14. 6BC4 Low Frequency Third-Order Intermodulation Characteristics.
Figure 12.15. 6BQ7 Low Frequency Third-Order Intermodulation Characteristics.
THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS FOR 6BY4 NO. K5

$E_b = 125V$
$E_f = 6.3V$
$f_1 = 35KC$
$f_2 = 45KC$
$F_{IM} = 25KC$

Figure 12.16. 6BY4 Low Frequency Third-Order Intermodulation Characteristics.
INTERMODULATION REJECTION CHARACTERISTICS FOR 5 TYPE 6J4 TUBES

\[ E_1 = E_2 = 0.5V \]
\[ E_b = 150V \]
\[ E_f = 6.4V \]
\[ F_{IM} = 27KC \]

TUBE LEGEND
- TUBE NO. 6
- TUBE NO. 7
- TUBE NO. 8
- TUBE NO. 10
- TUBE NO. 2

THIRD-ORDER IM REJECTION
FIFTH-ORDER IM REJECTION

Figure 12.17. 6J4 Low Frequency Third-Order Intermodulation Characteristics.
THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS
FOR FIVE EC-80/6Q4 TYPE TUBES

△ TUBE NO. 1
☐ TUBE NO. 2
● TUBE NO. 3
■ TUBE NO. 4
○ TUBE NO. 5

$E_f = 6.4V$
$E_b = 125V$
$E_1 = E_2 = .5V$
$F_{IM} = 27KC$

Figure 12.18 EC-80/6Q4 Low Frequency Third-Order Intermodulation Characteristics.
Figure 12.19. 417A Low Frequency Third-Order Intermodulation Characteristics.
Figure 12.20. 5876 Low Frequency Third-Order Intermodulation Characteristics.
GRID BIAS – volts

-3 -2 -1 0

○ TUBE NO. 1
● TUBE NO. 2
□ TUBE NO. 3
■ TUBE NO. 4

THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTIC FOR FOUR TYPE 6299

INTERMODULATION REJECTION – db BELOW 0.5 volts

E₁ = E₂ = .5V
Eₐ = 125V
Eₖ = 6.4V
F₈M = 27KC

Figure 12.21. 6299 Low Frequency Third-Order Intermodulation Characteristics.
Figure 12.22. 6386 Low Frequency Third-Order Intermodulation Characteristics.
UHF THIRD-ORDER INTERMODULATION REJECTION
FOR FIVE 6AF4 TRIODES

$E_b = 135\text{V}$
$E_f = 6.45\text{V}$

Figure 12.23. 6AF4 UHF Third-Order Intermodulation Rejection.
UHF THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS
FOR SIX 6AJ4 TRIODES

$E_b = 125V$
$E_f = 6.3V$
$F_{IM} = 300 mc$
$E_1 = E_2 = 100 mv$

Figure 12.24. 6AJ4 UHF Third-Order Intermodulation Rejection.
Figure 12.25. 6AJ4 Average UHF Third-Order Intermodulation Rejection.
UHF THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS
FOR FIVE 6AM4

$E_b = 210\text{V}$
$E_f = 6.45\text{V}$

Figure 12.26. 6AM4 UHF Third-Order Intermodulation Rejection.
UHF THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS FOR FIVE 6BC4

$E_b = 210V$
$E_f = 6.45V$

Figure 12.27. 6BC4 UHF Third-Order Intermodulation Rejection.
Figure 12.28. 6BC4 Average UHF Third-Order Intermodulation Rejection.
UHF THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS FOR SIX 6BY4

$E_b = 125V$

$E_f = 6.3V$

Figure 12.29. 6BY4 UHF Third-Order Intermodulation Rejection.
UHF THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS
FIVE TYPE 6J4 UHF TRIODES

- $E_b = 150$ volts
- $E_f = 6.4$ volts
- $F_1 = 295$ mc
- $F_2 = 290$ mc
- $F_{IM} = 300$ mc

Figure 12.30. 6J4 UHF Third-Order Intermodulation Rejection.
AVERAGE THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS AT UHF
TEN TYPE 6J4 UHF TRIODES

\[ E_b = 150 \text{ volts} \]
\[ E_f = 6.4 \text{ volts} \]
\[ F_1 = 295 \text{ mc} \]
\[ F_2 = 290 \text{ mc} \]
\[ F_{IM} = 300 \text{ mc} \]

Figure 12.31. 6J4 Average UHF Third-Order Intermodulation Rejection.
Figure 12.32. 5876 UHF Third-Order Intermodulation Rejection.
AVERAGE THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS AT UHF
SEVEN TYPE 5876 PENCIL TRIODES

\[\begin{align*}
E_b &= 215 \text{ volts} \\
E_f &= 6.4 \text{ volts} \\
F_1 &= 295 \text{ mc} \\
F_2 &= 290 \text{ mc} \\
F_{IM} &= 300 \text{ mc}
\end{align*}\]

Figure 12.33. 5876 Average UHF Third-Order Intermodulation Rejection.
Figure 12.34. 6299 UHF Third-Order Intermodulation Rejection.
UHF THIRD-ORDER INTERMODULATION
REJECTION CHARACTERISTICS
FIVE TYPE 6386 REMOTE CUTOFF TRIODES

\[ E_b = 125 \text{ volts} \]
\[ E_f = 6.4 \text{ volts} \]
\[ F_1 = 295 \text{ mc} \]
\[ F_2 = 290 \text{ mc} \]
\[ F_{\text{IM}} = 300 \text{ mc} \]

Figure 12.35. 6386 UHF Third-Order Intermodulation Rejection.
AVERAGE UHF THIRD-ORDER INTERMODULATION REJECTION CHARACTERISTICS
TEN TYPE 6386 TUBES

\[ E_b = 125 \text{ volts} \]
\[ E_f = 6.4 \text{ volts} \]
\[ F_1 = 295 \text{ mc} \]
\[ F_2 = 290 \text{ mc} \]
\[ F_{IM} = 300 \text{ mc} \]

Figure 12.36. 6386 Average UHF Third-Order Intermodulation Rejection.
Figure 12.37. Grid Mixer (Fourth-Order) Intermodulation Rejection Characteristic for 6AF4A No. 1.
GRID BIAS – volts

-5 -4 -3 -2 -1 0

- 100 - 90 - 80 - 70 - 60 - 50 - 40 - 30 - 20 - 10 - 0

Mixer (fourth-order) intermodulation rejection for 6BQ7 No. 7

Fourth-order frequencies

E_b = 125V
f_1 = 52KC
f_2 = 58KC
Local OSC = 30KC
F_{IM} = 27KC

Figure 12.38. Mixer Fourth-Order Intermodulation Rejection for 6BQ7.
MIXER (FOURTH-ORDER) INTERMODULATION REJECTION FOR 5670

\[ F_{IM} = 16\text{KC} \]

FOURTH-ORDER FREQUENCIES

\[ f_1 = 52\text{KC} \]
\[ f_2 = 58\text{KC} \]
\[ f_{osc} = 30\text{KC} \]

Figure 12.39. Mixer Fourth-Order Intermodulation Rejection for 5670.
GRID BIAS – volts

-5 -4 -3 -2 -1 0

• FOURTH-ORDER HARMONIC REJECTION $E_1 = .5V$

○ FOURTH-ORDER INTERMODULATION REJECTION $E_1 = E_2 = E_{osc} = .5V$

SIGNAL OUTPUT AS MIXER

PLATE LOAD = 200Ω

MIXER (FOURTH-ORDER) INTERMODULATION CHARACTERISTICS FOR 6386 NO. 8

$F_{IM} = 16KC$

FOURTH-ORDER FREQUENCIES

$f_1 = 52KC$
$f_2 = 58KC$
LOCAL OSC = 30KC

$E_b = 125V$

Figure 12.40. Mixer Fourth-Order Intermodulation Rejection for 6386.
XII. APPENDIX

C. Schematics and Diagrams
Figure 12.41. Schematic Diagram of Test Chassis for Low Frequency Intermodulation Measurements.
Figure 12.45. Ferrite Attenuator Control Amplifier.
Figure 12.46. Ferrite Attenuator Power Supply.
Figure 12.47. Mechanical Attenuator Servo Amplifier and Power Supply.
Figure 12.48. Two Stage 6AJ4 R-F Amplifier and Mixer Model UHFA-B2.
Figure 12.49. Two Stage 5876 R-F Amplifier Model UHFA-B2.
Figure 12.50. Three Stage 6AJ4 Amplifier and Grounded Grid Mixer Model UHFA-M3.
Figure 12.51. Three Stage R-F Amplifier Model UHFA-MDL.
D. Notes on the Loss Mechanism in the Ferrite Attenuator

Recent investigations of ferrite characteristics\textsuperscript{19} have stressed the \textit{gyromagnetic} resonance phenomena. It has been pointed out\textsuperscript{20} that acceptable non-reciprocal (gyromagnetic) devices at frequencies as low as 500 mc await the development of more nearly ideal ferrite materials, and that non-reciprocal devices may not be realizable below 500 mc. Better understanding of the role of \textit{domain rotation} resonance might extend the lower limit of non-reciprocal devices to 200 mc.\textsuperscript{21} At the present state of the art, however, devices for operation at 220-400 mc will utilize other than gyromagnetic phenomena.

The region between 500 mc and 100 mc has received little attention and it is difficult to find mutual agreement between investigators on the theory of magnetic field dependent losses in this frequency region. The relative importance of domain wall movement, domain rotation, dielectric losses, hysteresis losses, etc., is not known. The picture is further obscured for the engineer by a dearth of information from the manufacturer about characteristics of his materials at frequencies above about 5 mc.

It is known\textsuperscript{22} that ferrites in low or zero magnetizing field will have large losses at frequencies defined by

\[ \gamma H = \omega = \gamma (H_a + 4\pi M_s) \]

where

- \( H_a \) = effective anisotropy field in oersteds
- \( \gamma \) = gyromagnetic ratio for a free electron
  \[ = 17.6 \times 10^6 \text{ rad/sec-oersted} \]
- \( 4\pi M_s \) = saturation magnetization value for the ferrite in gauss.

This so-called low-field loss is \textbf{not} non-reciprocal; i.e., the effect does not differ for r-f fields of opposite polarizations.\textsuperscript{20}
The anisotropy field, at any point in the ferrite, is a measure of the degree of the preferential direction of magnetization, and for the bulk material it can be associated with the steep (middle) portion of a B-H curve. A material with low anisotropy, a requirement for lossy behavior below 200 mc, could be expected to exhibit a relatively short mid-portion in its magnetization curve, and would probably have a relatively low maximum permeability. Unfortunately, the static values furnished by the manufacturer cannot be assumed to hold at UHF. Ferramic Q, however, which was found suitable for the attenuator built for this project, does exhibit a static $\mu_m$ of only 400, as compared to 4300 for Ferramic H. Information about $\mu_m$ at UHF would perhaps facilitate the choice of an optimum attenuator material.

Sensiper\textsuperscript{20} and others\textsuperscript{22,23} indicate that the low field loss should reduce essentially to zero with an applied field of 100 oersteds. To explain the existence of losses he observed in some of the materials with fields up to 500 oersteds, Sensiper postulated alternative loss mechanisms. The most attractive of these (for application to the UHF case) is simply that complete saturation does not obtain throughout some ferrites at 100 oersteds. Useful data for selecting an optimum ferrite would be a B-H curve taken at UHF. A desirable material would probably have a B-H curve with a slope rapidly approaching zero with increasing field. An attenuator using a material that completely saturates at 100 oersteds would require only $1/25$ the operating power that was found necessary when Ferramic Q was used.

Sensiper also points out that the dielectric losses, which are large for Ferramic H and small for ferramic Q, arise from ohmic (microscopic eddy current) losses. A primary requirement for a low insertion loss attenuator is very high ac as well as dc resistivity. The granular structure of a ferrite renders a
dc resistivity measurement unreliable as an indication of ac resistivity. Data on the ac resistivity at UHF, or even at a few megacycles, would be useful.

In summary, a ferrite intended for use in a UHF coaxial attenuator should exhibit low anisotropy, and it is tentatively deduced that this means a low value of maximum permeability. A high ac resistivity is necessary for low insertion loss. A material which completely saturates in an applied field of 100 oersteds or less would require 25 times less solenoid power than Ferramic Q, assuming equal zero field and equal saturation field loss characteristics. An additional desirable characteristic is a high curie temperature.