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NRL Report 4790
Copy No. 4

ANALYSIS FOR IMPROVING NOISE FIGURES OF COUNTERMEASURES RECEIVERS

[UNCLASSIFIED TITLE]

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August 15, 1956

DECLASSIFIED by NRL Contract
Declassification Team
Date: 21 MAR 2017
Reviewer's name(s): [redacted]
Declassification authority: NAVY DECLASS GUIDE/NAVY DECLASS MANUAL, 11 DEC 2012
08 SERIES

[redacted]

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8-13-57 D.J.B.

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CONTENTS

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ABSTRACT

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Since sensitivity is one of the most important characteristics of a countermeasures receiver, the microwave receivers, TN-139/ULR, TN-140/ULR, TN-141/ULR, and TN-142/ULR, of the AN/SLR-2 (Serial No. 53) were analyzed to determine the lowest noise figure possible and the limitations of the present design. The losses and excess noise characteristics in each of these receivers were analyzed independently to determine the necessary types of modifications for best noise figure. The final innovations consisted of redesigning the r-f input coaxial-line-to-cavity coupler for the TN-139/ULR and TN-140/ULR together with modifying the local-oscillator decoupling circuit in these two receivers and the TN-141/ULR. The design of the mixer incorporated in the TN-141/ULR is inadequate and should be replaced with the type used in the TN-130/APR-9. The investigation of the TN-142/ULR consisted mainly of analyzing the merits of different types of crystals to determine their effect on over-all noise figure. The characteristics of the broadband Sylvania 1N286 coaxial crystal seem sufficiently favorable to warrant a new mixer design to match its r-f impedance. The limitations of the type of design present in the receivers under discussion were formulated from empirical data taken of the input mismatch loss, preselector loss, r-f crystal impedance, and i-f crystal impedance of the units. From this data optimum design calculations were performed for the TN-140/ULR with the practical minimum over-all noise figure determined used as a reference for all the receivers. Practical minimum values of noise figure were approached at certain frequencies in both the TN-139/ULR and TN-140/ULR, but not in the other two receivers. Since this indicates that the modified mixer design is close to optimum in the TN-139/ULR and TN-140/ULR receivers, the limiting factor for minimum noise figure is r-f circuitry loss. Noise figure improvement will also ultimately be limited by r-f circuitry loss in the TN-141/ULR and TN-142/ULR receivers if the suggested modifications are used successfully. Every attempt should be made to improve the r-f circuitry loss of the individual receivers, but difficulty will be encountered because of the wide frequency ranges involved.

PROBLEM STATUS

This is a final report on one phase of the problem; work on this problem is continuing.

AUTHORIZATION

NRL Problem R06-02
Project No. NE 071-240-3
Bureau No. S-1702

Manuscript submitted June 22, 1956

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ANALYSIS FOR IMPROVING NOISE FIGURES OF COUNTERMEASURES RECEIVERS
[Unclassified Title]

INTRODUCTION

In the countermeasures field it is essential to have receivers with the lowest possible noise figure. The four microwave receivers of countermeasures receiving set AN/SLR-2 (Serial No. 53) have been investigated to determine the modifications necessary for each individual receiver to approach optimum receiver design. The four receivers have a combined tunable frequency range of 1.0 to 10.750 kMc and are designated by TN-139/ULR (1.0 to 2.60 kMc), TN-140/ULR (2.30 to 4.45 kMc), TN-141/ULR (4.30 to 7.35 kMc), and TN-142/ULR (7.05 to 10.75 kMc). The r-f sections of all four receivers consist of three cavities which are tuned by axial movement of the center conductors. An aperture coupler exists at the first cavity to receive the r-f energy from the antenna and at the final cavity to feed the mixer. In all the receivers, transition between the antenna cable and the input cavity is made through a coaxial-line-to-cavity coupler which consists of a coupling loop and a transmission line which tapers down to the dimensions of the connector used. The mixer design, which is essentially the same for all four receivers, is comprised of a coupling loop for the final cavity, a transmission line, and a local oscillator decoupling circuit which attaches to the center conductor of the transmission line. The end of the center conductor is formed to function as a part of the crystal holder. The decoupling circuit for the TN-142/ULR consists of a sleeve bushing in the local oscillator connector which acts as a shunting element while the decoupling circuit for the TN-139/ULR, TN-140/ULR, and TN-141/ULR is an L-pad with the same type shunting element and a series resistor which connects directly to the center conductor of the mixer. It will be seen that this location of the series resistor adds a serious discontinuity to the mixer. The mixers are of the unbalanced type and incorporate a 1N21B crystal in the lowest frequency receiver, a 1N23B in the two middle range receivers, and a coaxial 1N26 in the highest frequency receiver. The 160-Mc i-f preamplifier used in the receivers consists of four conventional cathode-grounded 6AK5 circuits.

The investigation of minimizing the noise figure of the receivers was made by analyzing the cause and effect of the losses and excess noise contributed by the r-f section, the mixer, and the i-f preamplifier. A theoretical study was made of the losses and excess noise to determine their minimum value for a practical design. These minimum values were sought by modifying the existing design of the r-f section, mixer, and i-f preamplifier. It is necessary in the course of this study to measure certain characteristics of the receiver such as preselector loss, r-f and i-f crystal impedance, and cavity impedance. Since these measurements are difficult to make at the operating frequencies under consideration a check was made on their validity by calculating the conversion loss of the crystal utilizing the data recorded and then comparing the result with that given in the manufacturer's specifications. Since a more thorough empirical study was made of the TN-140/ULR, these calculations and the optimum receiver design calculations presented in the Appendix were made for this receiver. The other receivers are analyzed using this receiver as a reference.

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OPTIMUM RECEIVER DESIGN

The minimum noise figure attainable in a microwave receiver is limited by the loss in signal circuitry prior to amplification and by noise generated in the receiver components. In most present superheterodyne microwave receivers, a crystal mixer is the first active network. Since an appreciable part of the signal loss and excess noise are contributed by the crystal mixer, its design is a primary factor in obtaining a low noise figure. Other factors affecting the receiver noise figure are the r-f circuitry loss and i-f preamplifier noise figure. These factors can be reduced to practical limits and measured in the receiver. The optimum receiver design which is derived by use of these practical limits can be achieved only when the crystal mixer design is optimized.

The receiver noise figure can be expressed as

$$F = L_r L_c \left(F_i + t_m - 1\right) \tag{1}$$

where L_r is the r-f circuitry loss, L_c the mixer conversion loss, F_i the i-f preamplifier noise figure, and t_m the mixer noise temperature factor. For minimum F, each of the right-hand terms in Eq. (1) should be minimized, or if there are interdependences, these must be determined and the product minimized.

The r-f circuitry loss, L_r, includes preselector and antenna connection losses. The preselector losses can be broken down further to mismatch and insertion losses, but by proper design the latter can become of secondary importance in comparison to the former. There is a practical limit to which these losses can be reduced since the particular receivers under consideration operate over a broad frequency range. It is quite difficult to obtain a VSWR of less than 2.0 over a frequency range of 2 to 1 at these design frequencies; for instance, the VSWR of the individual r-f tuning heads studied is greater than 2.0 at many frequencies. Furthermore, it has been shown both theoretically and empirically that in order to achieve minimum noise figure a mismatch must exist at the crystal input terminals which gives additional mismatch losses. If a realistic average VSWR of 2.5 is assumed at the r-f input to the first cavity and at the r-f output of the final cavity feeding the crystal, then if perfect coupling is assumed between the first and second cavity and the second and third cavity, the maximum preselector average power loss would be 3 db. Actually this latter figure is low because perfect coupling does not exist between cavities and the insertion loss of the three cavities of about 1 db was not taken into account. The possibility of attaining the minimum preselector power loss by having the proper phase characteristics at the individual mismatch terminals to cause a complete cancellation of the losses is slight because of the number of mismatch points. It has been found that when the mismatches in the preselector are of the order mentioned in the above example, the minimum preselector loss is about 4 db.

The conversion loss L_c is difficult to minimize because its value is a function of numerous impedance conditions. Conversion loss is defined as the ratio of the maximum available power from the r-f source to the maximum available output power. Consequently, if the r-f source impedance and the impedance of the mixer, which includes the input circuit of the i-f preamplifier, are not operated over image-impedance* conditions the conversion loss will increase since the actual power input is less than the maximum available power.

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*"Image-impedance" is used in a network sense and should not be confused with image-frequency impedance.

Therefore, there must be a mismatch at the r-f signal source and crystal mixer junction for minimum conversion loss. The optimum degree of mismatch is a function of conversion loss of the crystal. If, for example, the crystal in use has a representative conversion loss of 6 db then the theoretical value (1) of VSWR would be 1.7.

The properties of the crystal material obviously have considerable effect on the conversion loss. It is convenient to express the E-I curve of a crystal as

$$i_f = k\,e^x \quad (e>0)$$

and

$$i_b \cong G_b e \quad (e<0)$$

where i_f is instantaneous forward current; i_b is instantaneous back current; k is a proportionality constant similar to conductance; x represents a nearly constant slope, d(log i)/d(log e), of the forward portion of the E-I curve plotted in logarithmic coordinates; and G_b is the nearly constant back conductance. Typical values of k and x for a 1N21B or a 1N23B crystal are 0. 05 and 2, respectively. Generally the conversion loss decreases as x and R_b increase. The value of x varies with the applied voltage and usually increases for increasing peak currents up to about 1 ma, and decreases for higher peak currents. Obviously, one way to regulate x is to control the amplitude of the local oscillator voltage. Maximum values of x are attained when the local oscillator excitation provides approximately 0. 2 to 0. 7 ma of rectified current to the crystal. Crystal current can vary between the limits 0. 2 to 2 ma without serious consequences. Although the application of negative bias to the crystal will also increase x, caution should be exercised since negative bias also increases the excess noise generated in the crystal. The former method of controlling x is used in the receivers under investigation.

By definition, conversion loss is a function of the impedance of both the r-f source and the mixer; hence any deviation of either from the optimum match condition would result in less than maximum available power. The r-f circuits used in the receivers under discussion offer a certain amount of impedance to the image frequency signal at the crystal terminals. This is the result of the image frequency impedance being effectively zero at the aperture of the final cavity feeding the mixer, owing to the high Q of the cavity, but being transferred to a higher impedance at the crystal terminals since the length of the transmission line in the crystal mixer design is an appreciable part of a wavelength. The image frequency signal referred to here is not an externally impressed, interfering signal, but is created internally as a by-product of the heterodyne process. It is produced when the i-f signal beats with the local oscillator fundamental, and also when the r-f signal beats with the second harmonic of the oscillator. Strum (1) develops conversion loss equations for three particular image frequency match cases:

(1) when the image terminals are short-circuited,

(2) when the external impedance at the image terminals is equal to the r-f source impedance (matched-image terminal conditions), and

(3) when the image terminals are open-circuited.

The last condition gives conversion losses of approximately 1 db less than the first two when average crystals are used.

The lowest possible noise figure for the i-f preamplifier is desired in the optimum design of the receiver. The fact that F_i - 1 is directly proportional to frequency indicates the desirability of low values of intermediate frequency. It will be seen, however, that t_m increases as the intermediate frequency decreases; therefore a compromise must be sought. Other factors that influence the choice of intermediate frequency will be discussed later. Two different types of low-noise i-f preamplifiers designed at 160 Mc were utilized to minimize the receiver noise figure. The first was the new Collins preamplifier design which incorporates two grounded-grid 417A triodes followed by a pair of conventionally operated 6AK5 pentodes. This preamplifier, as used in the TN-140/ULR, had a noise figure of 4.8 db when the input coil was optimumly tapped. The second consists of three cascaded cascode stages with 5718 triodes (2). This preamplifier was used in the TN-139/ULR and TN-141/ULR investigations. By optimizing the input tap the lowest possible noise figure of this preamplifier was about 6 db. Since the optimum tap setting for best receiver noise figure is slightly different owing to its effect on conversion loss, the actual noise figure of the preamplifier in the circuit is about 1 db higher than the afore-mentioned figure.

The last term of Eq. (1) is the mixer noise temperature factor, t_m, which is defined as the ratio of the actual noise power generated by the mixer to the noise power generated at room temperature by a resistance equal to the mixer output resistance. This figure does not include noise due to the local oscillator since in a good mixer design only a negligible amount of noise is contributed by the local oscillator. The mixer noise temperature factor for the receivers under investigation is quite different from the figure that is given in a manufacturer's specification sheet which is measured at 30 Mc in a standard mixer. The value of t_m at a specific signal frequency is a function of the intermediate frequency, the current passed through the crystal, and the physical design of the mixer which dictates under which of the three afore-mentioned image frequency conditions the crystal will operate. The dependence of t_m on the latter condition is obvious through its definition since the i-f output impedance of the crystal is a function of the image frequency termination. It has now been shown (1), through use of a composite curve on independent excess crystal noise measurements, that an inverse frequency relationship exists from 30 cps to 24,000 Mc. Using this relationship an exact optimum intermediate frequency can be chosen resulting in the lowest possible value of t_m and F_i as shown for the TN-140/ULR in the Appendix.

Caution should be used to prevent the local oscillator from contributing a considerable amount of noise at this optimum intermediate frequency. The local oscillator produces noise voltages on either side of the carrier. The spectrum in reflex klystron oscillators is determined by the cavity Q and the reflector voltage setting. The noise components which differ from the carrier frequency by an amount equal to the intermediate frequency mix with the carrier in the crystal and produce noise in the output, the amplitude of this noise being proportional to the local oscillator power. It is evident that the higher the intermediate frequency, the less effective noise in the spectrum and the smaller amount of converted noise. Reflex klystrons operating at 3.0 kMc sometimes produce an appreciable amount of noise at an i-f of 30 Mc, but at an i-f of 160 Mc the oscillator noise is negligible providing the crystal current remains less than about 2 ma. The latter condition is extremely important since the crystal (t_m-1) value is small compared to the i-f preamplifier noise figures obtainable at 160 Mc, and any increases of (t_m-1) due to oscillator noise would minimize the effect of obtaining a lower F_i. It should be noted that the precautions discussed pertaining to local oscillator excess noise are needed mainly because of the unbalanced mixer utilized in the receiver under investigation. A balanced mixer eliminates local oscillator noise; therefore if such a mixer is used the intermediate frequency can be decreased without an increase in local oscillator noise.

The TN-140/ULR receiver was analyzed at 3.0 kMc to determine the optimum intermediate frequency and the amount of decrease in over-all noise figure when the intermediate frequency of 160 Mc is decreased to its optimum value. The calculations in the Appendix indicate that the improvement in receiver noise figure is approximately 1.8 db for this particular receiver when the intermediate frequency is changed to the optimum value of 57 Mc. The reflex klystron of the TN-140/ULR would most likely not add an appreciable amount of excess noise at 57 Mc, thus allowing this increase in sensitivity without much trouble. This intermediate frequency, however, would have to be common to all four receivers, and although about the same amount of sensitivity improvement would be attained, the higher frequency reflex klystrons in the TN-141/ULR and TN-142/ULR could contribute excessive local oscillator noise at 57 Mc, thereby nullifying the gain achieved. Although a balanced mixer could be employed to remove this noise, it is extremely doubtful whether an increase of about 1.8 db in sensitivity is worth the added complexity of design. Furthermore, smaller values for the intermediate frequency increase the problem of external image rejection which is an important characteristic of a countermeasures receiver. It can therefore be concluded that the present value of 160 Mc and the present mixer configuration are the most practical in these receivers.

EXPERIMENTAL PROCEDURES

The r-f preselectors of the four receivers under discussion were aligned as advised in the instruction book before any investigation was made of the receivers. The maximum sensitivity was sought at each individual frequency check point while still satisfying bandwidth requirements. The obvious fact that this alignment is extremely important cannot be overemphasized since it is the controlling factor of noise figure once the mixer and i-f preamplifier have been specified. Re-alignment is usually essential when the local oscillator reflex klystron has been replaced.

All the noise figures recorded in this report were made by utilizing a "hot body" with the gaseous discharge of a fluorescent tube supplying the elevated temperature. This method is independent of bandwidth. Caution should be exercised if the cw method is used to measure F, for erroneous results can be attained if the bandwidth is not considered very carefully. The form of noise figure equation used for the cw method is the ratio of equivalent noise voltage of the receiver to the equivalent noise voltage of an ideal receiver. The latter is the thermal noise voltage of the antenna impedance, usually 50 ohms, and is represented by $\sqrt{4KTBR}$. The terms K and T represent Boltzmann's constant and absolute temperature in degrees Kelvin, respectively. The noise bandwidth, B, is of particular interest since its evaluation defines the accuracy of the noise figure measurement. Noise bandwidth is defined as

$$\left(\frac{1}{A_{max}}\right)^2 \int_0^\infty [A(f)]^2 \, df$$

where A(f) is the voltage gain as a function of frequency and A_{max} is the maximum of A(f). The determination of B is obvious from the definition, but it is not difficult to see that humps in the voltage response curve, A(f), would be exaggerated by the square relationship which in turn would cause the noise bandwidth to be much smaller than the original 3-db points of the response curve. Abnormally low values of F would be attained at a specific frequency if the cw measurement was taken at the maximum response point of one of these humps and the B considered as that when a flat response was present. To obtain valid noise figure data the noise bandwidth should be determined carefully and care should be taken that the frequency response does not vary appreciably between measurements.

The noise source (3) used in the TN-139/ULR investigation utilized a fluorescent tube with a helical coaxial winding to provide the impedance match. Noise figure data were taken with this source over the range of 1.0 to 1.70 kMc where the input source VSWR was less than 1.15. This would allow a discrepancy between minimum and maximum power loss due to noise source and r-f input mismatch of approximately 0.5 db. Possible variations larger than this could seriously impair the accuracy of the results especially when some improvements in sensitivities are of the order of 1 db. The accuracy of any one particular point up to 1 db could be disputed if all is being considered. However, if extreme care is exercised in making these measurements and if checks are made at a reasonable number of frequencies, a valid trend certainly can be attained.

The noise figure measurements of the TN-140/ULR, TN-141/ULR, and TN-142/ULR were made utilizing Kay Electric Company Microwave Mega-Node noise sources, the RG-48/U from 2.6 to 3.95 kMc, the RG-49/U from 3.95 to 5.85 kMc, the RG-50/U from 5.85 to 8.20 kMc, and the RG-51/U from 7.05 to 10.0 kMc.

All r-f VSWR and impedance measurements were made utilizing slotted line techniques. All i-f crystal impedance measurements were made using a General Radio type 1602-B UHF Admittance Meter with the local oscillator power output at the same level used in the noise figure investigation.

INVESTIGATION OF TN-140/ULR

A considerable amount of empirical data was taken on the TN-140/ULR to facilitate finding the limitations of this system of design. In addition to r-f input mismatch and noise figure investigations, r-f circuitry loss and crystal i-f and r-f impedance measurements were recorded. A Sylvania 1N23D silicon crystal marked "x" was used in the noise figure investigations. This selected crystal results in an average 1 db increase in sensitivity over a group of 1N23B's over the frequency range.

The initial modification of the TN-140/ULR was that of altering the input r-f coaxial-line-to-cavity coupler design. The purpose of this modification was threefold. It would improve the input match, would allow RG-9A/U cable to be used in place of the lossy RG-58A/U, and would incorporate a type N connector on the coupler to allow the tuning head to be removed from its enclosure without removing the r-f coupler. It can be seen in Table 1 that an average increase of 1.5 db in sensitivity can be expected over the frequency range when the 5 feet of RG-58A/U used as the antenna cable in this receiver is replaced by the same amount of RG-9A/U.

TABLE 1
Comparison of Antenna Cable Losses

R-F Cable Type	Loss at 1.0 kMc		Loss at 2.60 kMc		Loss at 4.40 kMc	
	db/100 ft	db/5 ft	db/100 ft	db/5 ft	db/100 ft	db/5 ft
RG-9A/U	8.6	0.43	16	0.8	24	1.2
RG-58A/U	22	1.1	41.5	2.08	61	3.05

The sketch of the coupler designed together with the VSWR of this and the original coupler is shown in Fig. 1. An attempt was made to decrease the serious mismatch conditions at both ends of the frequency range by using a 50-ohm transmission line and optimizing the loop penetration. As is evident in Fig. 1 this was accomplished to a limited extent but only at the cost of slight additional mismatch at the center frequencies. A

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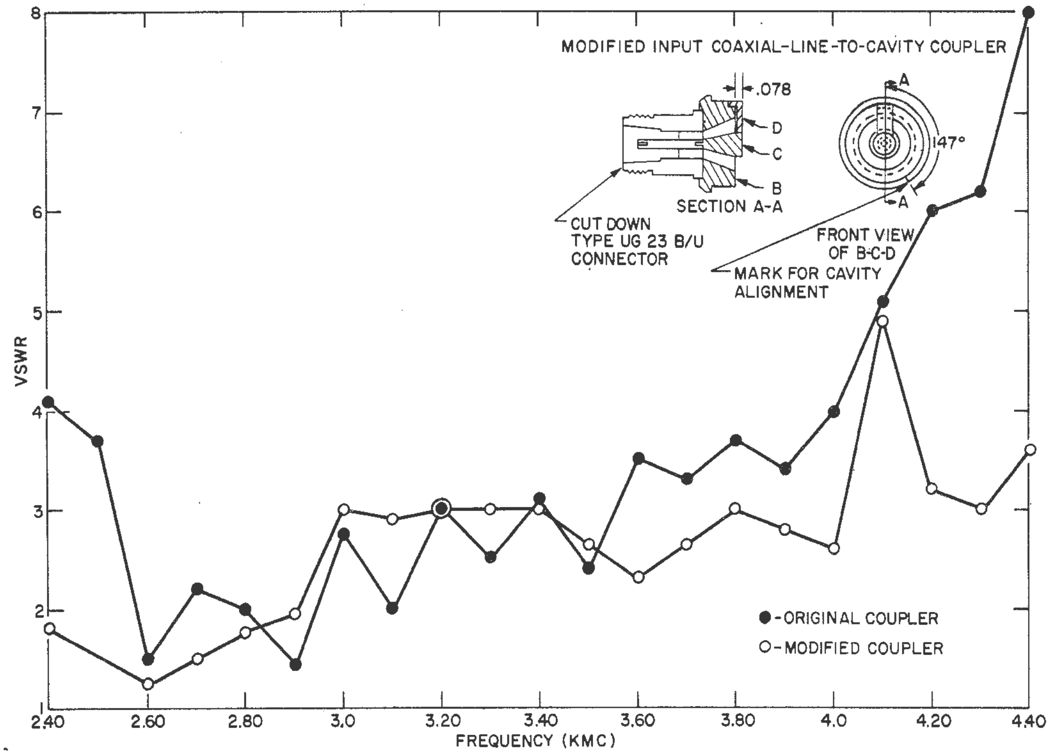

Fig. 1 - Effect of modified coupler on the r-f input VSWR of the TN-140/ULR

thorough empirical investigation of different types of r-f aperture couplers designs for the best matching conditions over the frequency range was not performed. Needless to say, further investigation to decrease these losses could be well warranted. One of the reasons why a good match is difficult to attain in the TN-140/ULR cavities is that the aperture is a relatively large distance from the short end of the cavity. The proper cavity impedance must then be attained through deep loop penetration which increases discontinuities in the magnetic field thereby increasing matching problems. The TN-129/APR-9, which is analogous to this receiver, has a smaller distance from the aperture to the short; therefore the loop has to be just flush with the cavity wall for a proper impedance match which results in a better and less sensitive match. Both the loop penetration necessary in the TN-140/ULR (0.078 in.) and the position of the loop in the cavity are quite critical. The former should be kept within 0.005 in. and the latter, although marked, should be checked with a slotted line, making slight angular adjustments if necessary.

A high impedance is required at the point where the local oscillator power is injected to keep the r-f signal voltage developed across the crystal as high as possible. A decoupling network, which is used in the TN-140/ULR mixer to achieve this impedance and also to attenuate the local oscillator power, consists of an L-pad with 51 ohms as the series element and a polyiron bushing as the shunt element. The position of the resistor seems to add a serious discontinuity to the system. By removing the series element and replacing it with a piece of No. 28 wire, an appreciable improvement in noise figure can be obtained throughout a good portion of the frequency range. In order to keep the local oscillator power at a reasonable level it was necessary to make an adapter with a series element and place it between the reflex klystron cavity coupling loop and polyiron bushing. In the adapter, the base of a type

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UG-88/U cable plug was soldered to the base of a type UG-291/U panel jack with the series resistor soldered to the individual pins. It was found that for this receiver a series resistor of 240 ohms attenuated the local oscillator power to a level where optimum operation could be approached. Curves I and II of Fig. 2 illustrate the improvement in noise figure when the adapter and modified mixer are used.

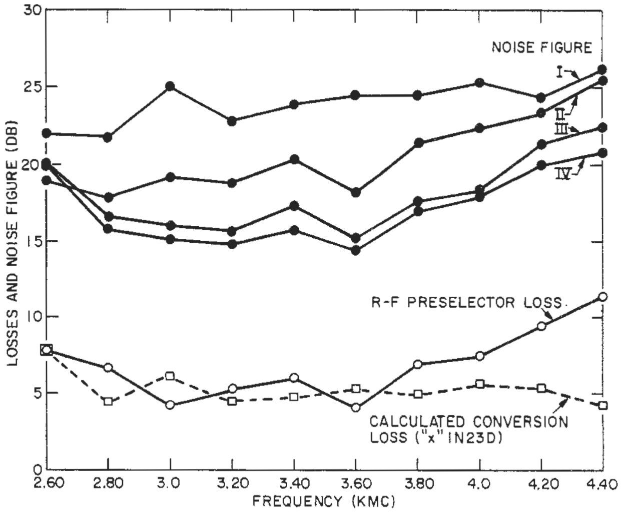

Fig. 2 - Noise figure, r-f preselector loss, and conversion loss for TN-140/ULR. The noise figure of the original TN-140/ULR with the "x" 1N23D crystal and the modified coupler (as shown in curve I) was progressively improved by using the modified mixer with the 240-ohm adapter (II) plus replacing the original i-f preamplifier with the new Collins preamplifier, using the original input tap setting (III) and then optimizing the tap (IV).

The fact that the modified mixer resulted in a higher impedance at the oscillator injection point is verified by Fig. 3, which shows the r-f impedance at the input terminals of the crystal under both conditions. The r-f impedance was measured, utilizing slotted line techniques, by placing a special adapter in the crystal holder and assuming that the stray capacitance (approximately 10 $\mu\mu$f) at the end of the holder represented a short circuit at these frequencies. Since the r-f impedance is then in effect due to the parallel combination of the r-f cavity impedance and that of the local oscillator coupling circuit, an increase in impedance would obviously indicate an increase in the latter since the former would remain constant at a certain frequency setting. Actually the stray capacitance represents an impedance of approximately 5 ohms over the range which evidently has some effect at lower frequencies, but this does not alter the over-all validity of the results. It should be noted that the increase in cavity impedance with frequency shown in Fig. 3 should be expected because with the stationary coupler the magnetic coupling decreases with frequency resulting in a higher impedance terminal. Attaining a higher impedance by replacing the series element with a small wire can be explained by considering the low impedance polyiron bushing as being transformed to a high impedance at the r-f crystal injection point by the incorporated transmission line. Since a large characteristic

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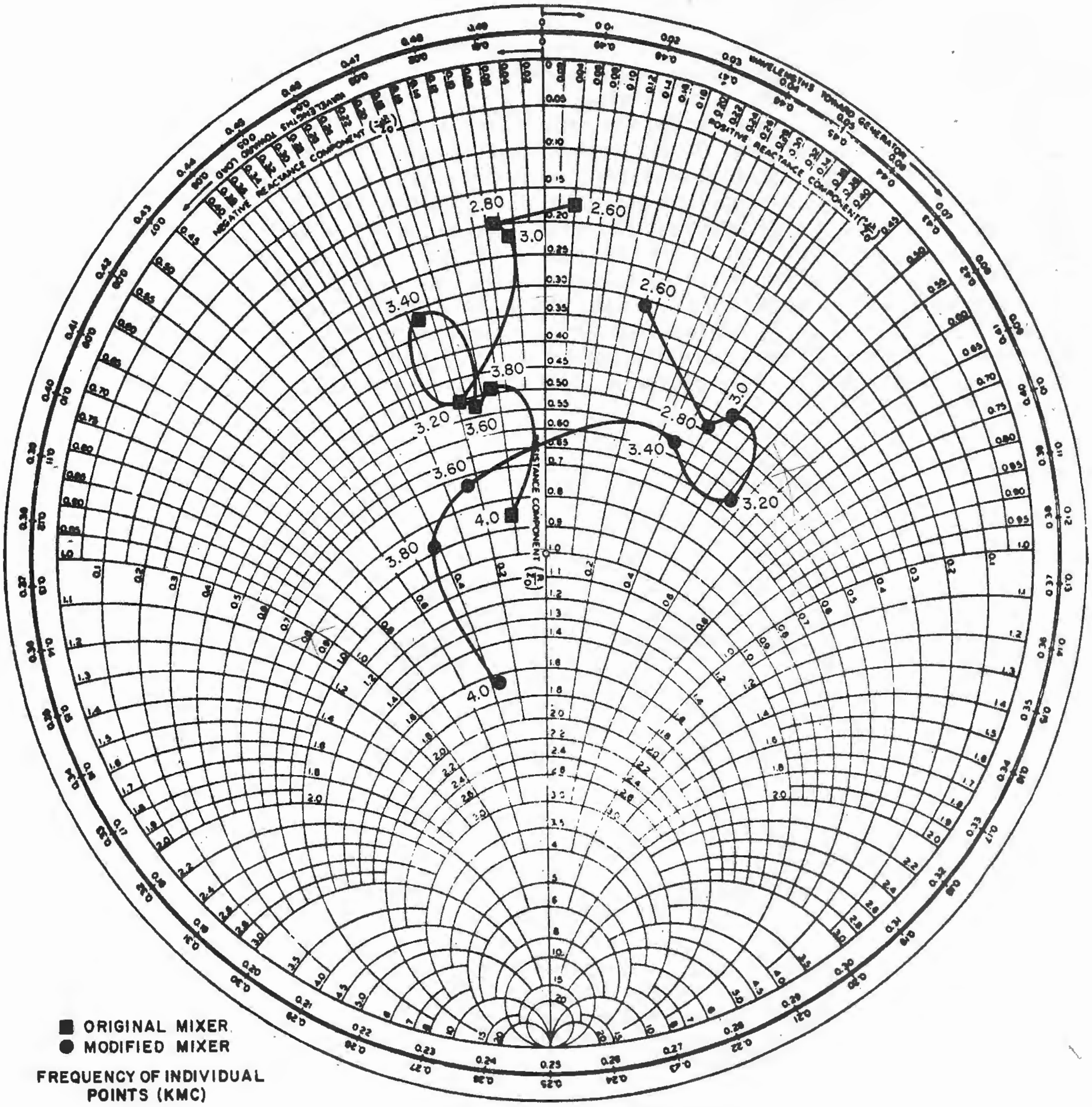

Fig. 3 - Measured r-f impedance of original and modified mixer and three cavities at crystal junction

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impedance of the line is essential in attaining a high local oscillator impedance, the center conductor should be made as small as possible.

A comparison was made between the latest Collins i-f preamplifier for the TN-140/ULR and the original preamplifier. Before accurate measurements of F_i could be made, the empirical value of i-f impedance of the crystal in the particular mixer used had to be determined. It is assumed that the reactive component is tuned out by the input of the preamplifier; therefore the impedance of the noise source will be the real component of the i-f impedance. As shown in Fig. 4, the average value of i-f impedance over the range seems to be of the order of 100 ohms for the "x" 1N23D in this mixer and also 100 ohms for the six 1N23B crystals at 4.0 kMc. With a noise source resistance of 100 ohms, F_i of the original and of the new Collins preamplifier were 8.8 and 5.5 db, respectively. The input tap of the latter was not optimum for this particular receiver, apparently having been adjusted by assuming the crystal had a nominally higher i-f impedance than measured here. Hence, by moving the input tap on the tube side of the first 417A one turn toward the cathode, the F_i was decreased to 4.8 db. This resulted in the same order of decrease in receiver noise figure as shown by curves III and IV of Fig. 2. Except at 2.60 kMc where a resonant effect of the local oscillator adapter caused excessive losses, the average variation in receiver noise figure between curves II and IV of Fig. 2 was close to 4 db, the same as the difference between the two preamplifiers. This should be expected when local oscillator noise is minimized.

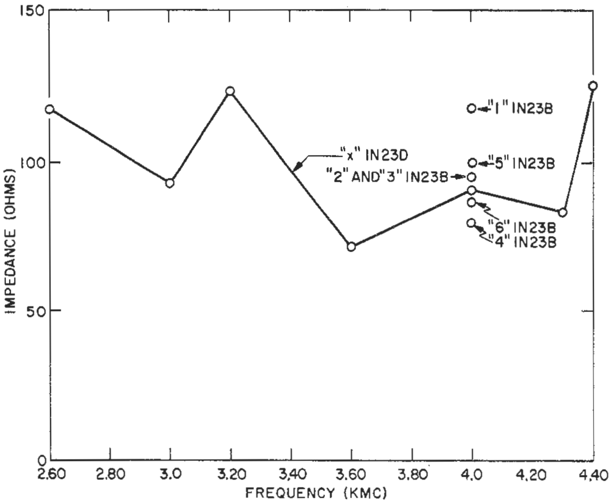

Fig. 4 - Real components of i-f impedance measured over the frequency range for the "x" 1N23D crystal and at 4.0 kMc for six marked 1N23B crystals in the modified mixer of the TN-140/ULR

The exact losses in r-f preselectors must be known in order to evaluate the limitations of this receiver design. Valid measurements of this type at these frequencies are extremely difficult to make. Since the substitution technique of loss measurements is most practical here, the mixer loop coupler and transmission line had to be reproduced with a type N fitting replacing the crystal holder. In order to guarantee that the losses measured were due to the preselector alone, the mixer losses had to be minimized. Because of the previously discussed modification of the local oscillator series element, the local oscillator injection impedance was considered high enough not to seriously disturb the crystal match condition. Therefore, its omission in the reproduced mixer did not neglect appreciable r-f losses. A thorough investigation of the original mixer design was made and with the change in the local oscillator series element, the design seemed optimum. This investigation was comprised of loop penetration variations with both the original mixer and a modified mixer design. The latter innovations consisted of changing the transmission line characteristic impedance to 40 ohms from the original 88 ohms and varying the aperture size to obtain the best over-all noise figure. The center conductor was also varied with aperture size to maintain a 40-ohm characteristic impedance. This was done to determine whether a lower impedance transmission line would provide a better match to the crystal. Since the Q of the individual cavities, which is governed by the coupling device used, must be approximately equal for suitable passband response, the Q equation* of a coaxial tuner loaded by one loop (4) was the design criterion. The best noise figure obtained with the 40-ohm transmission line was about the same as that of the original mixer. A slight improvement was expected, since r-f measurements indicate that the crystal impedance is lower than 88 ohms. A possible explanation of the lack of apparent improvement with this modification is indicated by the Q equation. The area (A) of the loop which is decreased by reducing the characteristic impedance must be counterbalanced by an increase in loop depth (decrease in r) in order to stabilize Q at a certain impedance; the added loop depth discontinuity losses can more than offset the slight improvement in noise figure expected.

The loading of the special mixer adapter for preselector loss measurements had to be the equivalent of the r-f crystal impedance. The r-f crystal impedance can be derived from the r-f impedance data recorded if optimum matching in the mixer is assumed. This assumption is reasonable for the TN-40/ULR modified mixer especially at the frequencies such as 3.2 kMc and 3.60 kMc where the receiver noise figure approaches the theoretical statistic minimum given in the Appendix. Under optimum mismatch conditions the r-f signal impedance should be approximately 0.59 times the mixer impedance; therefore from Fig. 3 the r-f crystal impedance of the "x" 1N23D in this mixer seems to be of the order of 50 to 60 ohms. This simplified the loading problem since 50-ohm type N connectors and lossy cable could be used as the load without introducing serious errors in the loss measurements. In comparing the preselector losses with the noise figure of the TN-140/ULR (Fig. 2), it is evident that the same general trend exists in each curve. Conversion loss varies as the matching conditions differ at various frequencies so a direct proportionality between the curves should not be expected. The validity of the data taken was checked by comparing the L_c of the manufacturer's specifications to the L_c calculated from Eq. (1) with L_r and F taken from Fig. 2 and with F_i and t_m being 3.02 and 1.24 (at 160 Mc), respectively. From Fig. 2 it can be seen that the average L_c of the 1N23D over the frequency range was 5.3 db. Since the manufacturer's specification gives an L_c of 5 db at 10.0 kMc and since this value of L_c can also be obtained at lower frequencies under conditions of optimum mismatch, the methods utilized in the measurements are verified.

With the previously discussed modifications made on the TN-140/ULR, it follows from calculations similar to those in the Appendix that the lowest practical noise figure expected should be about 14.1 db; this assumes a practical minimum of 4 db for r-f circuitry loss, 5.0 db for conversion loss, and 4.8 db for F_i. As evidenced in Fig. 2, the above noise figure was approached at 3.20 and 3.60 kMc.

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*$Q = \left(\frac{\pi z_0 n}{4}\right) \left(\frac{r^2 R_g}{A^2 \mu_0^2 f^2 \cos^2 \theta}\right)$

The possibility of realizing this value of noise figure over the entire range without a reduction in the preselector loss is remote because of the unmatched variations in the cavity and crystal impedance with frequency. It has been shown here that for available crystals all terms of Eq. (1) have been minimized with the possible exception of the r-f circuitry loss which is the limiting factor in this design. It is doubtful if much improvement can be made in this figure because of the wide frequency range of the TN-140/ULR, but further investigation in the input r-f coupler design should be made. The higher preselector loss at the extreme ends of the band may be attributable to bandwidth deficiencies of the inter-cavity aperture couplings.

INVESTIGATION OF TN-139/ULR

The input r-f coaxial-line-to-cavity-coupler design of the TN-139/ULR was modified for the same reasons as for the TN-140/ULR. In this case, an average reduction of 0.98 db in r-f circuitry loss over the frequency range is achieved when 5 feet of RG-9A/U replaces the same amount of RG-58A/U (Table 1). A decrease in input mismatch was sought by replacing the varying characteristic impedance of the original input coupler by that of a constant characteristic impedance of 50 ohms and empirically determining the loop penetration for optimum matching conditions. The VSWR of the original and modified input coupler together with the design of the latter is shown in Fig. 5. The loop penetration into the cavity is critical; hence, to guarantee satisfactory results the loop depth should stay within 0.005 in. of the stipulated value, 0.094 in. Some type of resonant effect causes considerable mismatch at the lower end of the frequency range. Varying the loop penetration has little effect on this condition. Improvement of this situation could be sought through innovations in loop geometry. Obtaining a good input match for this receiver over a 2.6 to 1 frequency range is difficult; therefore if a serious attempt is made to improve the match at the extreme low frequency end, care should be taken that the match through the rest of the range is not impaired.

The L-pad in this receiver consisted of a 240-ohm series resistor and a polyiron bushing shunting element. By replacing the resistor with No. 28 wire and utilizing the same type adapter used for the TN-140/ULR with a 100-ohm series resistor on the opposite side of the polyiron bushing, a maximum improvement in receiver noise figure of about 2.5 db was attained (curves I and II in Fig. 6). A rough check not included in Fig. 6 was also made with the original and modified mixer from 1.70 to 2.60 kMc. At all the frequencies checked (every 100 Mc) an improvement in noise figure was obtained when the modified mixer was used.

A slightly higher value of resistance, greater than the 100-ohm series element used, would have been desirable since the crystal current was somewhat high in certain sections of the frequency range, but a resonant effect decreased the local oscillator power at the lower frequencies, thereby resulting in high noise figures. The latter effect is evident in Fig. 6. The poorer sensitivity at the low end may also be attributable to additional preselector losses which are the result of a phase change in the r-f crystal impedance due to the mixer modification. This possible high additional loss is more likely to appear at the lower frequencies owing to the prodigious r-f input mismatch as shown in Fig. 5.

The noise figures of the original and improved i-f preamplifier (triple-cascode) in the TN-139/ULR were 9.1 db and 7.5 db, respectively. An average improvement in sensitivity of slightly less than the difference of the preamplifier noise figures (curves II and III of Fig. 6) is attributed to local oscillator noise of the reflex klystron which is due to somewhat high power levels. The over-all noise figures recorded here seem to agree

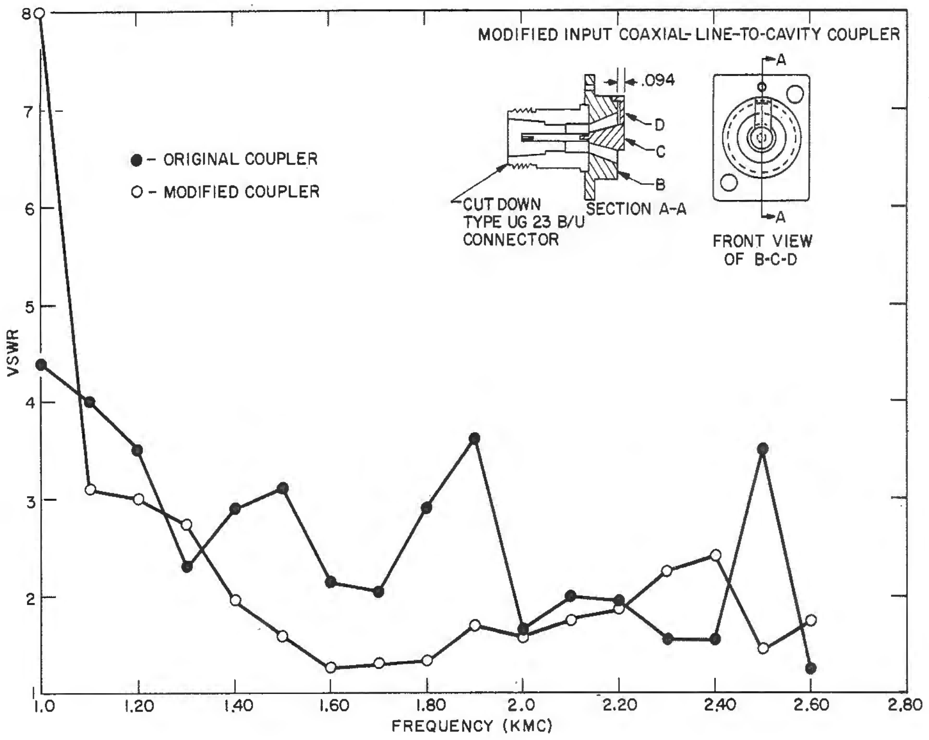

Fig. 5 - Effect of modified coupler on the r-f input VSWR of the TN-139/ULR

quite well with the best that can theoretically be expected with this particular system. The sensitivity calculations for the TN-140/ULR in the Appendix can be used as a direct comparison since the crystal characteristics described there are reasonably close to the "A" 1N21B silicon crystal used in this investigation. For example, if the F_i of 6.06 db used in the calculations is replaced by an F_i of 7.5 db, then the receiver noise figure would be about 16.8 db; this figure would be about 1 db higher if the L_c difference between the 1N21B and 1N23D is considered. A measured low of 15.8 db was obtained at 1350 Mc (Fig. 6); the fact that this figure is lower may be attributed mainly to the preselector losses of 4 db assumed in the theoretical case. This was a good assumption for the TN-140/ULR where the input VSWR is rather high, but since over most of the frequency range the input match of the TN-139/ULR is reasonably good, values of L_r close to 2 db can be obtained. This comparison proves that with the crystals and i-f preamplifiers available, optimum theoretical design figures were reached; therefore any further improvement must come through minimizing r-f circuitry losses throughout the entire range.

INVESTIGATION OF TN-141/ULR

The input VSWR of the TN-141/ULR (Fig. 7) was measured at the antenna terminal at the back of the r-f tuning head. It is evident that the input match deficiency warrants a complete investigation of a different type r-f input coaxial-line-to-cavity coupler design. At certain frequencies the VSWR seems to be abnormally high, but this most likely is due to odd phasing conditions between mismatches at the connectors for the r-f input and

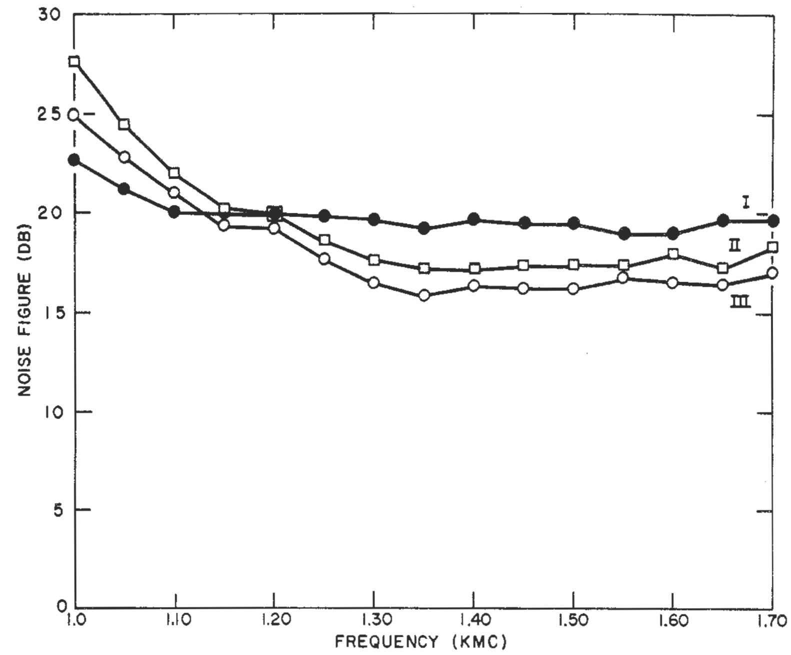

Fig. 6 - Noise figure of TN-139/ULR. The noise figure of the original TN-139/ULR, using the "A" 1N21B crystal and the modified coupler (as shown in curve I), was progressively improved by using the modified mixer with the 100-ohm adapter (II) plus replacing the original i-f preamplifier with the triple-cascode i-f preamplifier (III).

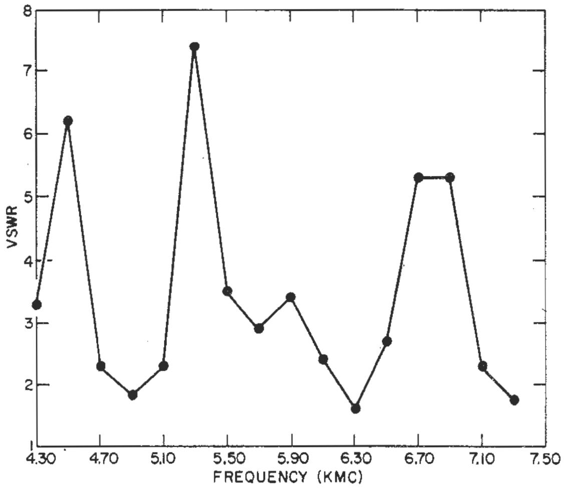

Fig. 7 - The r-f input VSWR of the TN-141/ULR

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for the measurement setup. No attempt was made to redesign the input r-f aperture coupler since RG-9A/U antenna cable was used in this tuning head.

Noise figure measurements of this receiver (Fig. 8) indicate that the mixer design is completely inadequate. The oscillator series resistor in the mixer impedes the r-f energy flow considerably. By replacing this series element, as was done in the other r-f tuning heads, with a No. 28 wire and placing an adapter similar to that used in the TN-140/ULR on the oscillator side of the carbon-impregnated bakelite shunting element, considerable improvement in sensitivity was attained (curves I and II, Fig. 8). The same value resistor that was used as the series element in the original pad (47 ohm) was utilized in the adapter. Although a higher value of resistance was desired to keep the local oscillator power output at optimum levels through most of the band, difficulty in attaining adequate local oscillator power from the 5721 reflex klystron at higher frequencies restricted this value.

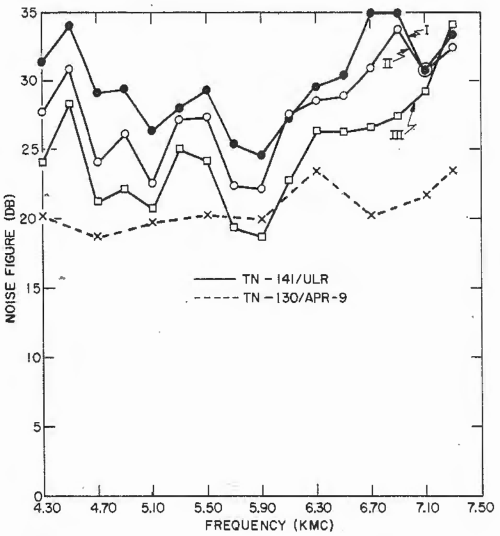

Fig. 8 - Comparison of the noise figure of the TN-141/ULR with that of the TN-130/APR-9, using the triple-cascode i-f preamplifier. The noise figure of the original TN-141/ULR with the "x" 1N23D crystal (as shown in curve I) was progressively improved by using the modified mixer with the 47-ohm adapter (II) plus replacing the original i-f preamplifier with the triple-cascode i-f preamplifier (III).

The preamplifier in this r-f tuning head has an F_i of 11.5 db or about 2.5 db higher than the original preamplifiers in the other heads. Of course this is partly responsible for the higher noise figure of this receiver, but even with the 7-db improved (triple-cascode) preamplifier, the over-all noise figure is far from the theoretical minimum. The crystal impedance (300 ohms) used to determine F_i was the average of the values of i-f impedance measured for the "x" 1N23D over the frequency range (Fig. 9). From a comparison of the i-f impedance of the same six 1N23B crystals used in the TN-140/ULR investigation at 5.10 kMc (Fig. 9) with that at 4.0 kMc (Fig. 4), it is interesting to note the marked difference in i-f impedance in the TN-140/ULR and TN-141/ULR mixers. Although the modified preamplifier is of the order of 4.5 db better than the original preamplifier the average improvement in receiver noise figure when the former is used is about 3 db. This is the result of local oscillator power being greater than optimum over a considerable part of the range together with inaccuracies of measuring F_i because of the large i-f crystal impedance variations.

The circuitry loss of the r-f section over the frequency range was checked by the same method as described for the TN-140/ULR. The assumption was made that the 1N23D crystal had an r-f impedance of approximately 50 ohms at these frequencies in this particular crystal holder. The verification of this impedance could not be made as was done for the TN-140/ULR mainly because it could not be assumed that the crystal mixer design was optimum. However, some r-f impedance measurements were made in the frequency region around 5.90 kMc where optimum design could have been approached, and the crystal impedance seemed to be in the vicinity of 50 ohms. The average r-f circuitry loss over the frequency range was

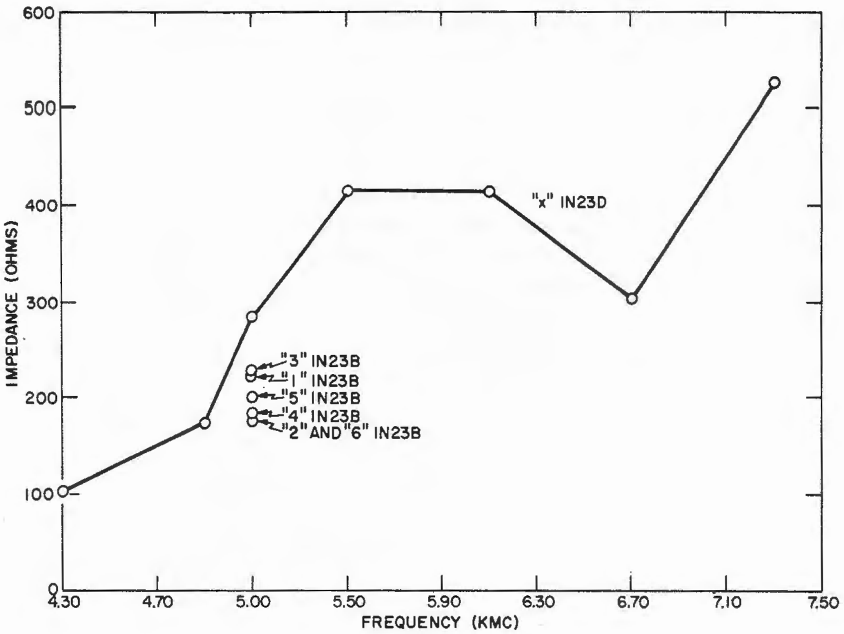

Fig. 9 - Real components of i-f impedance measured over the frequency range for the "x" 1N23D crystal and at 5.10 kMc for six marked 1N23B crystals in the modified mixer of the TN-141/ULR

7 db. The theoretical values calculated indicate that with an L_r of 4 db and an F_i of 7 db, optimum designed receivers should have an approximate over-all noise figure of 16.2 db. The average F of the TN-141/ULR under optimum conditions with an average L_r of 7 db should be approximately 19.2 db. In this particular case when the same 1N23D crystal was used in both receivers under consideration, the latter figure is slightly low because it does not take into account the decrease in rectification efficiency with frequency which is the result of the increase in barrier susceptance. This value for F was mentioned just as a guide to determine when optimum mixer design was being approached. It was further assumed in this figure that when the cavity impedance is once optimized with crystal impedance both impedances will have the same variations with frequency. This is difficult to attain since the properties of the crystal itself are involved; therefore allowances in F should be made for additional mismatches throughout the band.

The crystal mixer of the type found in the TN-130/APR-9 is far superior in design to the one under discussion. Since the r-f preselectors of the TN-130/APR-9 and TN-141/ULR are fundamentally the same and cover the same frequency range, the merits of the individual crystal mixers can be compared provided both preselectors are aligned in the same manner and the same i-f preamplifier is used. This was done and the comparison is shown in Fig. 8. Although the average value of F of the TN-130/APR-9 lacks by about 2 db the optimum average expected, it is considerably better than that of the TN-141/ULR. The main difference in the two mixers is in the local oscillator coupling. In the TN-130/APR-9 the decoupling circuit consists of just a polyiron slug, and a common loop suffices for r-f pickup and local oscillator coupling. The merits of this type of decoupling circuit were seen in this report when the series element was replaced by a piece of wire. The common loop method of coupling not only eliminates a discontinuity in the mixer transmission line but also removes the frequency sensitive portion of transmission line between the r-f coupling loop and local oscillator coupling contact.

INVESTIGATION OF TN-142/ULR

The investigation of the TN-142/ULR consisted mainly of modifying the mixer to accommodate type 1N23B crystals and comparing the merits of various 1N26 crystals in the original mixer. The r-f input match at the antenna receptacle at the rear of this tuning head was also analyzed with the results shown in Fig. 10. The match could be considered adequate but room for improvement exists and every opportunity to decrease r-f circuitry losses should be made. No attempt was made to improve the design of the r-f input coaxial-line-to-cavity coupler.

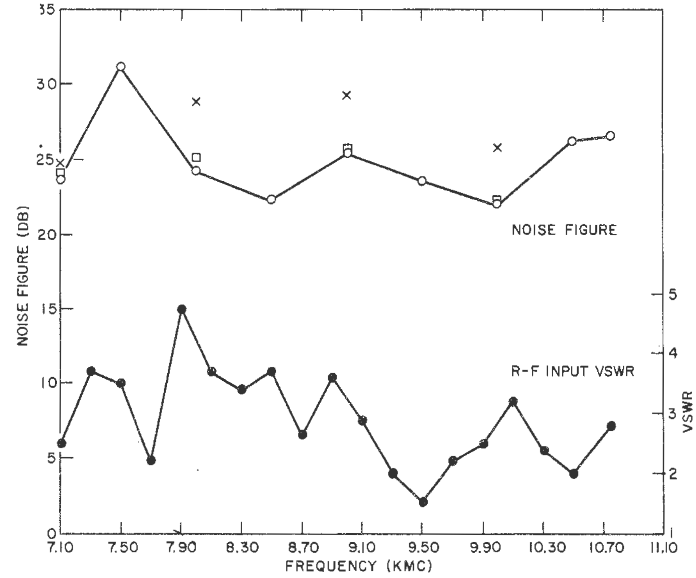

Fig. 10 - Noise figure and r-f input VSWR of TN-142/ULR and comparison of the average noise figure obtained, using six W.E. 1N26 crystals(□) and five Sylvania 1N26 crystals (X)

In the TN-142/ULR the coaxial 1N26 silicon crystal, which was designed to operate at 24.0 kMc, is used as the conversion element. The conversion loss of this crystal in the frequency range of the TN-142/ULR is very difficult to define. This is mainly due to the erratic r-f impedance fluctuations that exist in this crystal at other than the design center frequency. Affecting this impedance is the frequency-sensitive bead of dielectric which is a half wavelength at the design center frequency and supports the center conductor; the impedance is also affected by the crystal and cat whisker properties and prefabrication techniques. Obviously, as close to an optimum match as possible should be made to minimize conversion loss.

The noise figure of this receiver was measured with a Western Electric 1N26 used in the original mixer together with the original i-f preamplifier which had an F_i of 9.4 db

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(Fig. 10). Attempts to improve the noise figure by varying the loop penetration of the mixer were unsuccessful. The choice of a crystal for this receiver can be critical because of the discontinuities mentioned above. This point is illustrated in Fig. 10 where the average noise figures of six W. E. 1N26 crystals and five Sylvania 1N26 crystals and compared at four frequencies. Although the average deviation of 2.8 db is appreciable, it should be realized that this investigation was made to emphasize that the choice of a crystal could be important and should not be construed as indicating that all W. E. 1N26 crystals are better than those of Sylvania in this mixer. A statistical study should be made before the latter statement could be verified and such a study was not attempted.

A coaxial-type mixer was designed which would hold the 1N23D (or 1N23B) cartridge for this receiver in order to determine if this crystal, which was designed to operate at 9.375 kMc, would lead to a better receiver noise figure. An optimum mismatch was sought by varying various parameters of the mixer, but with little success. A standard waveguide mixer is used by the manufacturer to achieve the 5-db conversion loss of the 1N23D at the above frequency. How this crystal would operate in such a mixer over the frequency range of the TN-142/ULR is open to conjecture. A waveguide mixer could not be used in this receiver because of the losses of the necessary coaxial-to-waveguide transition. A point of interest is that crystals designed to operate at a frequency in the band do not seem to yield sensitivities over the band as good as those of crystals designed for a higher frequency. This situation is apparent in the TN-142/ULR, where a 1N26 is used, and also in the other receivers, where a 1N21B designed for 3.060 kMc is used in the TN-139/ULR and a 1N23D or 1N23B is utilized in the TN-140/ULR and TN-141/ULR. One explanation of this phenomenon is that the mixer design was not optimized for the crystals in question. Another explanation could be seen through r-f impedance considerations since the barrier capacitance, which is a function of the properties of the silicon and size of the cat whisker, has to be smaller for crystals designed at higher frequencies to obtain the maximum rectification efficiency; therefore in a frequency range below the design frequency, the variation in r-f impedance would be less, thereby simplifying matching problems.

The noise figure of the TN-142/ULR was checked with Sylvania crystals of the coaxial type, 1N286 and 1N78, in the original mixer. The former is a broadband crystal which operates from 10.0 to 22.0 kMc with a maximum VSWR of 3.0 in a standard 65-ohm waveguide mixer. This match is accomplished mainly by substituting an undercut bead for constant characteristic impedance in the crystal transmission line in place of the frequency sensitive half-wave bead section. The 1N78 crystal is designed for 16.0 kMc and has a maximum VSWR of 3.0 over the region of 10.0 to 16.0 kMc. The investigation showed that the noise figures obtained using these two crystals did not reach that using the W.E. 1N26. This should be expected, since the r-f impedance of each type crystal is different. In order to examine these crystals properly, other mixers should be designed to match their particular r-f impedance characteristics. This investigation should be attempted especially in the case of the 1N286 since the removal of the bead discontinuity could certainly decrease the conversion loss over the frequency range. Some doubt may arise as to validity of this approach, because it can be shown that the W.E. 1N26 used here has about the same conversion loss as the Sylvania 1N286 at 10.0 kMc. The 1N286 has a conversion loss of 7.6 db (5) at 10.0 kMc when measured in a 65-ohm standard mixer. A conversion loss of 7.5 db at 10.0 kMc could be calculated for the 1N26 from Eq. (1) if a value of L_r of 5 db is assumed together with an F_1 of 9.4 db and an F of 22 db (Fig. 10). This can be surmised as indicating that optimum mixer design exists, but it is quite possible that the removal of the bead discontinuity present in the 1N26 would enhance optimum mismatching over the entire frequency range and not cause such variations in sensitivity with different crystals as were discussed earlier. Therefore, an investigation into the design of a mixer suitable for the 1N286 would be well warranted.

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High local oscillator power levels cause excessive noise in certain portions of the TN-142/ULR frequency range. This condition cannot be cured through attenuation since the 2K48 klystron would not provide adequate power over the entire frequency range if any attenuation is inserted. Since there is no terminating attenuating bushing in the local oscillator cable, the local oscillator power is dependent on the r-f impedance of the cavities and crystal. Therefore, if a modification in mixer design is contemplated, local oscillator termination is a factor.

SUMMARY AND CONCLUSIONS

Optimum mixer design for a receiver is achieved when the specifications of the crystals in use are met. If, together with the optimum mixer design, the best available i-f preamplifier is utilized, the minimum practical over-all noise figure is achieved with any further improvement coming from the remaining limiting factor, r-f circuitry loss. Further improvements in crystal characteristics and i-f preamplifier noise figure to decrease the minimum receiver noise figure are, of course, possible; but the optimum design defined here is derived from available crystals and i-f preamplifiers. The two low noise i-f preamplifiers used in this investigation showed marked improvement over the original preamplifier. The cascode preamplifier (2) had a noise figure of 7 to 7.5 db depending upon the i-f impedance considered. The new Collins preamplifier with optimum tap adjustment had a noise figure of 4.8 db in the TN-140/ULR.

The 1N21B, 1N23B, and 1N26 crystals originally used in the receivers under discussion were all designed for single frequency operation. In this application, the problem of obtaining optimum matching over the wide frequency ranges of the individual receivers would be considerably facilitated if the crystals used had broadband r-f impedance characteristics. It seems from the data recorded in Fig. 2 on the TN-140/ULR that the Sylvania 1N23D has reasonably broadband characteristics in this frequency region since the conversion loss is reasonably constant over the frequency range with the receiver noise figure being more of a function of r-f circuitry loss. The broadband properties of the other crystals cannot be established because of lack of data, but an attempt could be made to obtain such data from the manufacturer.

The theoretical minimum noise figure was approached in the TN-139/ULR and the TN-140/ULR receivers. This was accomplished by minimizing mixer losses by attaining a high impedance local oscillator injection point through modification of the original local oscillator decoupling circuit. This modification consisted of replacing the series resistor by a No. 28 wire, and placing an adapter with a series resistor between the shunt element and the reflex klystron cavity to attenuate the oscillator power to the levels required for optimum operation. This resulted in the optimum mixer design, whereby further improvement in over-all noise figure could be achieved only by decreasing r-f circuitry losses. Some decrease in L_r was obtained in the TN-139/ULR and TN-140/ULR by redesigning the r-f input coaxial-line-to-cavity coupler. The new couplers decreased the input mismatch, allowed the replacement of the lossy RG-58A/U cable by RG-9A/U cable, and made possible the removal of the r-f tuning heads from their dust covers without removing the input r-f coupler. There is still considerable room for improvment in the input match for these receivers, and although the matching problems are complicated by the broad frequency ranges involved every attempt should be made to minimize the mismatch losses further. Although no attempts were made to improve the design of the input couplers of the TN-141/ULR and TN-142/ULR receivers, the input VSWR curves of these receivers (Figs. 7 and 10) indicate that a more suitable input r-f coupler design is needed.

The mixer design in the TN-141/ULR is not optimized when the same type of local oscillator decoupling circuit innovation discussed above is used. Although this modification results in some improvement, theoretical optimum design noise figures are not obtained. The basic design of this mixer is faulty and it has been shown that a mixer of the type used in the TN-130/APR-9 more nearly approaches the optimum design. Thus, the limiting factor of the present TN-141/ULR design is dependent upon the combination of mixer and r-f circuitry losses.

The selection of the proper crystal seems to be the main problem in sensitivity considerations for the TN-142/ULR. Although the receiver noise figures measured utilizing a W.E. 1N26 were reasonably good at certain frequencies, inconsistency over the frequency range and variations in different crystal models were serious drawbacks. The latter two inadequacies seem to be the result of discontinuities in the 1N26 structure in the frequency region of the TN-142/ULR, causing optimum r-f impedance mismatching over the range to be extremely difficult. The broadband Sylvania 1N286 could possibly be the solution to the problems, but since the 1N286 and 1N26 have different r-f impedance characteristics it would be necessary to design another mixer.

RECOMMENDATIONS

1. All possible efforts should be made to decrease the mismatch at the r-f input of all four receivers. The modified r-f input coaxial-line-to-cavity couplers designed for the TN-139/ULR and TN-140/ULR should replace the original couplers until more efficient ones are designed.

2. The local oscillator series element discontinuity in the mixer should be removed from field receivers in the TN-139/ULR, TN-140/ULR, and TN-141/ULR which have mixers of the type discussed here. Since this innovation in the TN-139/ULR results in the least improvement in noise figure, this is the most dispensable. The mixer modifications described in this report are simple in nature; therefore they can be installed in the field by technicans.

3. The crystal mixer design of the TN-141/ULR, serial No. 53, is inadequate. A crystal mixer of the type used in the TN-130/APR-9 receiver should be considered if a new design is contemplated.

4. An attempt should be made to use one of the recently designed broadband crystals in the TN-142/ULR receiver. The Sylvania coaxial 1N286 is in this category. A crystal mixer should be designed for optimum mismatch to the r-f impedance of this crystal.

ACKNOWLEDGMENTS

The constructive suggestions of Mr. H. K. Weidemann and Mr. G. M. Bullock provided invaluable aid toward the completion of this project.

* * *

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APPENDIX
Optimum Receiver Design Calculations

Characteristics of the TN-140/ULR receiver at 3.0 kMc are utilized in calculating the optimum receiver design. Some of the information incorporated in the article by Strum* was used as a basis for these calculations. The optimum intermediate frequency is determined together with observing the effect on receiver noise figure when the frequency is changed to 160 Mc.

Since a conversion loss of 5 db should be obtainable for the Sylvania 1N23D under optimum mismatch conditions at 3.0 kMc, this figure was used as a practical value of L_c for optimum design calculations. The r-f circuitry loss L_r is represented by 4 db. The noise temperature factor t_c of this crystal at an intermediate frequency of 30 Mc was assumed from published specifications to be 1.7. Since the noise temperature factors measured in standard test sets at 30 Mc are usually made approximately at matched-image-frequency terminal conditions, Fig. 11 of Strum* was used to transpose this figure to open-image-frequency terminal conditions, which is believed more suitable in this particular mixer; this gave a value for t_m of 2.3 at 30 Mc.

The optimum value of intermediate frequency together with the value of t_m and F_i at this frequency can be determined from Fig. 13 of Strum.* Since the 6AK5 low-noise cascode i-f preamplifier frequency characteristics are utilized in Fig. 13, the noise figure of this preamplifier will be used in the theoretical calculations. Approximately 1 db should be added to this figure in the final analysis since the match for best F is different than the match for best F_i. The other types of low-noise preamplifiers used in this report will have essentially the same frequency characteristics as the 6AK5 cascode preamplifiers and will give approximately the same value of optimum intermediate frequency. For the purposes of determining the practical F for the four receivers under discussion, the appropriate value of F_i can be inserted in the equation.

Calculations of optimum intermediate frequency and over-all noise figure:

$$L_c = 5.0 \text{ db or } 3.16$$

$$t_c = 1.7 \text{ (at 30 Mc)}$$

$$t_m = 2.3 \text{ (at 30 Mc)}$$

$$IF_{opt} = 57 \text{ Mc}$$

$$t_m = 1.7 \text{ (at 57 Mc)}$$

$$F_i = 10 \log 1.7 + 1 = 3.31 \text{ db or } 2.14$$

$$L_r = 4 \text{ db or } 2.51$$

$$F = L_r L_c (F_i + t_m - 1)$$

$$= 2.51 \times 3.16\ (2.14 + 0.7) = 22.6 \text{ or } 13.54 \text{ db}$$

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*P. D. Strum, "Some Aspects of Mixer Crystal Performance," Proc. IRE 41:875-879 (July 1953)

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Calculations of over-all noise figure for an intermediate frequency of 160 Mc:

$$L_c = 5.0 \text{ db or } 3.16$$

$$t_c = 1.7 \text{ (at 30 Mc)}$$

$$t_m = 2.3 \text{ (at 30 Mc)}$$

$$t_m = 1.24 \text{ (at 160 Mc)}$$

$$F_i = 10 \log 3.2 + 1 = 6.06 \text{ db or } 4.03$$

$$L_r = 4 \text{ db or } 2.51$$

$$\begin{aligned} F &= L_r L_c (F_i + t_m - 1) \\ &= 2.51 \times 3.16 (4.03 + 0.24) = 33.9 \text{ or } 15.31 \text{ db} \end{aligned}$$

For this particular receiver these calculations indicate that a reduction of 1.77 db in F can be obtained if the intermediate frequency is reduced from 160 Mc to the optimum value of 57 Mc.

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