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A RADIO CORPORATION OF AMERICA SUBSIDIARY
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A DISCUSSION OF NOISE IN PORTABLE RECEIVERS

The trend toward improved performance of portable dry-battery-operated receivers has led to considerations of whether a tube additional to the normal 4-tube complement for such receivers can be used advantageously.

At the outset, it is self-evident that if increased gain is the only requirement for improved performance, the fifth tube should be added as an i-f stage. However, maximum gain may not be the only consideration, since the frequency converter stage when followed by high i-f gain may give rise to intermittent noises not predictable by tube and circuit theory. Using the additional tube as an r-f stage avoids this difficulty and is often preferable design practice for portable receivers utilizing dry-battery tubes. For this reason, this Note considers only the use of the fifth tube in an r-f stage.

On the basis that the fifth tube is a 1T4 used in a resistance-coupled r-f stage having a load resistance of 10000 ohms and a total shunt capacitance of 20 $\mu\mu$f, calculated gain values for the r-f stage are as follows:

Frequency	Gain per 1000 micromhos
600 kc	8.0
1000	6.2
1500	4.7

While higher values of gain may be obtained by the use of the 1T4 in the more expensive tuned r-f stage, a complete appraisal of the value of an r-f stage must include the matter of noise. However, before considering the noise, let us examine further the r-f gain on the basis of electrode current requirements.

Fig. 1 shows the effect of screen voltage on plate current, screen current, cathode current, and transconductance, for the 1T4. It will be noted that while the cathode current is nearly 5 milliamperes for a screen voltage of 67.5 volts, it is only 1.3 milliamperes for 30 volts, and that the corresponding values of transconductance are 900 and 600 micromhos. From the standpoint of minimizing B-battery current, the 30-volt condition is preferable. However, this condition of operation results in a moderate decrease in transconductance. Thus, for an untuned r-f stage at 600 kc, the gain is 8.0 x 0.6, or 4.8. At higher frequencies, the gains are proportionately less. Since the capacitance in shunt with the load resistor can not be reduced, it is apparent that resort must be had to tuned circuits to obtain improved gain per stage. As an illustration, a 1T4 used in a tuned r-f stage gave measured gain values for a transconductance of 600 micromhos as follows:

Frequency	Stage Gain
600 kc	12.5
1000	9.3
1500	6.0

In this stage, the plate circuit was tuned to 500 kc in order to increase the gain at the lower frequencies. This procedure tends to compensate for the decreased efficiency of a loop antenna at the lower frequencies.

Receiver Noise Measurements

A convenient method of determining the relative noise of receivers is to compare their equivalent noise side-band input (ensi) values. This method is used in the following discussion to compare two portable receivers, both having tuned loops and 1R5 converter stages, but one having a 1T4 tuned r-f stage. Although the following procedure is not based entirely on theoretical considerations, the equations (1), (2), and (3) are directly useful.

The thermal-agitation-noise voltage (rms) developed by a resistor is

$$2\sqrt{KTRf} \qquad (1)$$

where
K is Boltzman's constant of 1.372 x 10^{-23} joules per degree Kelvin
T is temperature in degrees Kelvin (usually 300°K)
R is resistance (ohms) when it, as usual, is substantially constant over a narrow bandwidth of frequencies
f is bandwidth in cycles per second

A tuned loop is assumed to develop thermal agitation noise as though it were a resistor having a pure resistance equal to its resonant impedance. This assumption does not lead to any serious error where the bandwidth of the receiver is not greatly reduced by the selectivity of the tuned loop. A tuned loop known to be typical for portable receivers, gave values of tuned impedance and Q as follows:

Frequency	Tuned Impedance of Loop Circuit	Q
600 kc	53000 ohms	84
1000	88000	79
1500	116000	61

The noise developed in a pentode (such as the 1T4) may be dealt with as though it were produced by a voltage impressed on the grid circuit of the tube. This noise-equivalent voltage, in turn, may be dealt with as though it were the thermal-agitation-noise voltage of a resistor. The value of this resistor is the noise-equivalent resistance and, for a pentode, may be readily calculated from the following expression.

$$\text{Pentode noise-equivalent resistance (ohms)} = \frac{2.5}{g_m} + 19.2 \frac{I_b I_{c2}}{I_a g_m^2} \qquad (2)$$

where

g_m is transconductance in mhos
I_b is plate current in amperes
I_{c2} is screen current in amperes
I_a is cathode current in amperes

An immediate advantage of the equivalent-resistance method is that the equivalent-noise resistance of a tube, the 1T4 for example, may be simply added to the noise-equivalent resistance of a tuned loop (or other input circuit), to determine the total noise-equivalent resistance for the loop and tube together. However, for a receiver circuit, a third component of resistance should be included in order to account for the receiver noise developed beyond the first tube.

At the grid of the following stage -- a 1R5 frequency converter in the present case -- a measurement (or calculation) of the equivalent-noise voltage (when the first tube, a 1T4, is cold) results in a noise-equivalent resistance which may be directly referred to the grid of the preceding tube by dividing it by the square of the r-f stage gain. This procedure gives the third component of noise-equivalent resistance for the entire receiver.

In this manner, values of noise-equivalent resistance are found for a typical loop used with the 1T4 r-f stage, and for the loop used with a 1R5 frequency converter. If these values of noise-equivalent resistance should be found to be equal, it would be evident that the use of the r-f stage does not reduce noise. A lesser value of noise-equivalent resistance with the r-f stage means, of course, a decreased value of ensi for that receiver. Since equation (1) shows that a resistor develops noise voltage in proportion to the square root of its resistance, the ratio of ensi for the receiver with the r-f stage to the ensi for the receiver without the r-f stage is

Square root of quotient
of equivalent resistance without r-f stage (3)
by equivalent resistance with r-f stage

The equivalent-noise resistance for the 1T4 at a screen voltage of 30 volts is shown in Fig. 1 to be 16500 ohms. Various measurements on the 1R5 at the same screen voltage (30 volts) show its equivalent-noise resistance to be approximately 200000 ohms throughout the broadcast band. The equivalent-noise resistance of the 1R5 varies with screen voltage in substantially the same manner as shown for the 1T4 in Fig. 1. While the noise of the 1R5 (or of any typical converter) is essentially the direct i-f noise, the result is as though the thermal agitation noise of a resistor (having a resistance equal to the noise-equivalent resistance of the tube) were impressed on the grid at the signal frequency.

Receiver Noise Calculations

In order to compare the performance of a portable receiver having either a tuned or an untuned r-f stage with a receiver without an r-f stage, it follows from the earlier discussion that the comparison must include noise as well as gain. The relative noise values for the different receivers can be calculated in the following manner. The receivers considered are

1. Receiver with 1R5 converter and no r-f stage.
2. Receiver with 1R5 converter and untuned r-f stage using 1T4 with plate load of 10000 ohms shunted by 20 $\mu\mu$f.
3. Receiver with 1R5 converter and tuned r-f stage using 1T4 and having gain values as reported earlier in this Note.

The 1T4 is assumed to have a transconductance of 600 micromhos. The tuned circuit between the 1T4 and the 1R5 is assumed to have an impedance value of 50000 ohms. This latter assumption simplifies the calculation, and is permissible because a large change in this value does not materially affect the final results.

The noise-equivalent resistance (R_o) for the receiver without r-f stage is simply the noise-equivalent resistance (200000 ohms) of the 1R5 plus that of the tuned loop. Hence, R_o for the various frequencies is as follows:

Frequency	R_o
600 kc	253000 ohms
1000	288000
1500	316000

The noise-equivalent resistance (R_t) for the receiver with tuned r-f stage is the noise-equivalent resistance (16500 ohms) of the 1T4 plus that of the tuned loop, plus that (referred to the grid of the 1T4) of the 1R5 and the circuit which couples it to the 1T4. Values of R_t follow:

Frequency	R_t
600 kc	70000 ohms
1000	107500
1500	139500

Equation (3) may be evaluated from the values of R_o and R_t, although the db improvement, 10 log (R_o/R_t) may be obtained directly, and is given below.

Frequency	Improvement with tuned r-f stage
600 kc	5.6 db
1000	4.3
1500	3.55

These values of db improvement are not subject to any substantial increase by raising the r-f gain, because the referred values of noise-equivalent resistance are already small in comparison with the combined noise-equivalent resistance of the loop and the 1T4.

For the receiver with the tuned r-f stage, the calculation was considerably simplified because the selectivity afforded by the tuned grid circuit of the frequency converter prevents any effective transmission of noise at the intermediate frequency, the image frequency, and at higher frequencies which have i-f separation from harmonic frequencies of the oscillator. However, these several components of noise must be considered for the receiver with the untuned r-f stage. In aggregate, they are quite detrimental. Moreover, the values of untuned r-f stage gain given earlier in this Note are considerably less than gain values for the tuned r-f stage. For these reasons, the noise reduction afforded by an untuned r-f stage is considerably less than that which may readily be obtained with a tuned r-f stage.

The case of an untuned r-f stage is considered by means of a numerical example showing the evaluation of the noise-equivalent resistance at 1000 kc. Results for 600 and 1500 kc are also given at the end of this Section.

For the assumed case of a 10000-ohm load, a 20 $\mu\mu$f shunt capacitance, and a transconductance of 600 micromhos, the following table shows the calculated r-f stage gain for the signal frequency of 1000 kc, an intermediate frequency of 455 kc, an image frequency of 1910 kc, and the higher frequencies of 2455 and 3365 kc. Inclusion of still higher frequencies would not materially affect the result.

	I-F	Signal	Image	Higher Frequencies	
Frequency (kc)	455	1000	1910	2455	3365
Stage Gain	5.2	3.73	2.3	1.85	1.38
Relative Gain	1.40	1.00	0.62	0.50	0.37

The 1T4 itself develops noise as though the thermal-agitation-noise voltage of a 16500-ohm resistor were impressed on its grid. However, a bandwidth factor must be used with this value of resistance so as to take into account the amplification of noise at all of the frequencies in the foregoing table. The 1R5 must also be considered in the process. Approximate ratios of 1R5 gain at the above frequencies to the gain at the signal frequency will be used as follows:

	Frequency	1R5 Relative Gain
I-F	455 kc	1.25
Image	1910	1.00
2nd H. Images	2455, 3365	0.60

These ratios are typical of most frequency-converter tubes when operated near optimum excitation.

The relative gain factors applicable to noise at the five frequencies considered are the products of the factors in the two previous tables. Their values are

Frequency (kc)	455	1000	1910	2455	3365
Relative Gain	1.75	1.00	0.62	0.30	0.22

The effective bandwidth applicable to the 1T4 noise is that which is applicable to the receiver as a whole, multiplied by the squares of these terms. Another way of arriving at the same result is to state that "the noise-equivalent resistance, considered to be effective at the signal frequency only, is the product of the noise-equivalent resistance of the 1T4 and the sum of the squares of these terms." This statement follows since the thermal-agitation-noise voltage of a resistor, impressed on the 1T4 grid in a manner which would exclude noise generated outside the band centered at 1000 kc, would produce the same result. Consequently, we can introduce the idea of an equivalent resistance for the 1T4 noise in an untuned stage. When the 1T4 is used in this circuit, the components of noise-equivalent resistance are as follows:

Frequency	Noise-Equivalent Resistance
455 kc	50000 ohms
1000	16500
1910	6300
2455	1400
3365	800

The total noise-equivalent resistance is 75000 ohms.

More than half of this total is caused by i-f amplification in the r-f stage. This may be prevented by connecting a suitable wavetrap across (or effectively across) the 10000-ohm load resistor in the plate circuit of the 1T4. When this is done, 50000 ohms is removed from the total value (75000 ohms), leaving 25000 ohms. This latter value of noise-equivalent resistance is used for the 1T4 instead of 16500 ohms when the noise-equivalent resistance for the entire receiver with untuned r-f stage is obtained.

The entire noise-equivalent resistance at the 1T4 grid includes 88000 ohms to account for the tuned loop, and 14400 ohms added to account for the 1R5 converter. The latter figure is the value referred to take care of the 200000-ohm noise-equivalent resistance of the converter. The result at the 1T4 grid is approximately 177000 ohms for a receiver without an i-f wavetrap, and 127000 ohms, with a wavetrap. The results with an untuned r-f stage are compared with the results when no r-f stage is used, in the table following this paragraph. Although the use of noise-equivalent resistances has avoided any necessity for a knowledge of bandwidth, these resistance values -- 177000 and 127000 ohms -- may be readily interpreted as actual noise voltages by means of equation (1), provided a bandwidth is given or assumed. In this matter, the noise bandwidth is twice the effective a-f bandwidth, because the r-f and i-f circuits and tubes develop noise throughout the entire range of frequencies occupied by the double side-band signal. Also, the effective a-f bandwidth is somewhat less than the apparent frequency coverage, because of the usual drooping or gradual cut-off at both the high- and the low-frequency ends of the a-f response curve. On an assumed basis of an effective a-f bandwidth of 5000 cycles per second, the noise-equivalent resistances of 177000 and 127000 ohms correspond respectively to noise voltages of 5.4 and 4.6 microvolts (rms).

Frequency	Improvement without i-f wavetrap	Improvement with i-f wavetrap
600 kc	3.2 db	4.5 db
1000	2.0	2.8
1500	0.7	2.6

Although the improvement factors are less than those obtained with the tuned stage, it is important to note that the improvement at the low-frequency end is still considerable, and that this is the range in which improvement is most needed because of the loss of loop sensitivity.

A word of caution is added to assist in dealing with likely discrepancies between calculated and measured data on noise improvement. The above table gives calculated results in db. The magnitudes are small, particularly at the high-frequency end of the broadcast band. When such data are taken, an error of 1 db is probable, except where a very highly refined technique is used. Accordingly, calculated results should be considered only as a guide to results obtainable in practice.

Conclusions

The decision as to whether an r-f stage can be used advantageously in portable receivers must give consideration to the degree of noise reduction which can be achieved by the r-f stage.

When a tuned r-f stage having only moderate gain is used, converter noise is quite unimportant and the result is a greater noise reduction than obtainable with the use of an untuned r-f stage. However, when an i-f wavetrap is used across the plate load circuit of the untuned r-f stage, the difference in noise is small.

The question of the efficacy of the untuned r-f stage deals with a border-line case, where the final decision may depend upon other considerations.

1T4

TYPICAL CHARACTERISTICS

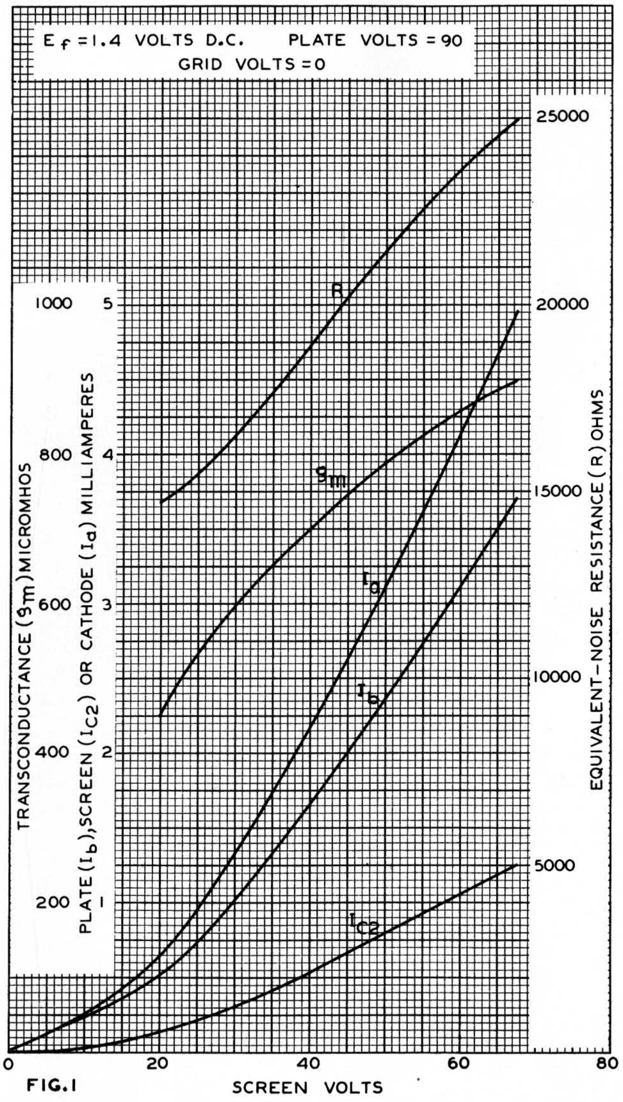

FIG. 1

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