

A SIMPLE RECEIVER ADAPTATION FOR VLF SIGNAL RECEPTION**E. O. UKEM**

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ABSTRACT

This paper presents a superheterodyne communications receiver that was adapted, through low-cost circuit modification, to the reception of signals in the Very Low Frequency (VLF) range. The radio frequency (RF) section of an existing High Frequency (HF) vacuum-tube based receiver was replaced with a transistorized circuit designed to operate at VLF. Also modified were the local oscillator and the antenna coupling circuits. The modified receiver was used, along with other components of a receiver system, to receive some VLF signal transmissions, thus establishing the possibility of receiving and utilizing such signals in the location.

KEYWORDS: Very Low Frequency, Receiver, Superheterodyne, Intermediate Frequency, Decoder

1. INTRODUCTION

The world today is an information bound society, in which the efficiency of production of wealth depends greatly on information. It is generally accepted that information is power. However, for information to be really useful, it has to be complete, accurate, relevant, and timely. Furthermore, it has to be available where it is needed. This implies that there are times when information needs to be transferred from one point to another – from source to destination. Obviously, the fastest means of such transfer is by radio communication and, not surprisingly, it is the most commonly employed means. The information to be transferred is converted to electrical form and used to modulate a carrier, which is then transmitted. At the destination the signal is received with appropriate equipment and demodulated or decoded, to recover the information. The three main methods of reception of radio signals are the Direct Gain Method, the Heterodyne Filter Method, and the Phase Locked Loop (PLL) Method. The PLL method is the most complex of the three, and also the most reliable, while the Direct Gain Method is the simplest. Whatever the method of reception employed, some kind of receiver is required in radio signal reception. These receivers may be quite sophisticated and, inevitably very expensive, depending on the application. This situation tends to limit the use of such receivers to the very serious professional users. Hobbyists and students are rather put off by the high costs involved. A simpler receiver system of reasonable accuracy would be an encouragement, at least to students desiring to explore further the use of the radio spectrum.

One class of information that often needs to be transferred from one place to another is time and frequency. Users of accurate time and frequency information abound everywhere, and the demand for such information is generally high the world over. Standard time and frequency information originates from precision atomic clocks kept at standards laboratories such as the International Bureau of Weights and Measures (Bureau International de Poids et Mesures, BIPM) in France. The information is disseminated to the users through radio communication, among others (Kartaschoff, 1978). Some areas where this information is applied include the calibration of electronic measuring instruments, synchronization of consumer electronics, frequency setting of broadcast equipment, synchronization of satellite communication terminals, synchronization of clocks on military vehicles, terrestrial and celestial navigation, observation of astronomical events, control of scientific processes, calibration of medical equipment, synchronization of power generation networks, and synchronization of surveillance systems.

The objectives of this paper are to present a superheterodyne communications receiver that was adapted to the reception of standard time and frequency signals in the

Very Low Frequency (VLF) range and highlight the different steps taken to set up the system.

2. Theory

For superheterodyne reception, the incoming radio signal (carrier plus information or intelligence) is converted into a signal of fixed frequency called intermediate frequency (IF). This conversion is achieved in the mixer circuit by mixing (i.e. beating or heterodyning) the incoming signal with the signal derived from a local oscillator within the receiver. In this process, beats are produced and the mixer produces a frequency equal to the difference between the local oscillator and the radio wave frequency. The circuit is so designed that the local oscillator always produces a selected frequency (very often 455 kHz) above or below the radio frequency (Mehta and Mehta, 2003). Therefore the mixer will always produce an intermediate frequency of 455 kHz regardless of the station to which the receiver is tuned. The production of a fixed intermediate frequency is the salient feature of the superheterodyne circuit. At this fixed intermediate frequency, the amplifier circuits operate with maximum stability, selectivity, and sensitivity (Schwartz, 1980).

To identify incoming radio signal frequencies, use is made of the relationship in the heterodyne principle, namely:

$$f_o = f_i \pm f_s \quad (1)$$

where f_o is the local oscillator frequency

f_i is the intermediate frequency

and f_s is the incoming signal frequency.

For any given incoming signal frequency, two values of f_o are possible – one above and one below the intermediate frequency. It is therefore the absolute value of the difference between f_i and f_o that gives the incoming signal frequency. That is,

$$f_s = |f_o - f_i|$$

$$\text{or } f_s = |f_i - f_o|$$

In practice, f_o is chosen to be above f_i and the form of the equation generally used is therefore $f_s = |f_o - f_i|$. This choice is determined by the required capacitor tuning range, which should be kept within practicable limits. The intermediate frequency signal, which still contains intelligence, is then fed into a detector, to extract the information. The

extracted information is displayed appropriately for use as desired.

The VLF range was selected for this work because signals in this range are known to be relatively steady, being available round the clock and also globally. Propagation characteristics do not vary much with time of day or with season, as is the case with higher frequencies. This is because propagation at VLF is achieved mainly by ground waves, and does not depend on reflection from the ionosphere, whose height above ground varies with time of day and with seasons.

3. MATERIALS AND METHODS

The equipment used in this work included an amplitude-modulated vacuum-tube based super-heterodyne G.E.C communications receiver type BRT 400 B, a locally designed and constructed 1m x 1m square loop antenna, a

signal generator, a frequency counter, an oscilloscope, and a loudspeaker. The G.E.C. receiver was originally designed to operate at Low, Medium and High Frequencies (LF, MF and HF), with a frequency range from 160 kHz to 30 MHz, and an intermediate frequency of 455 kHz. The operating frequency range was not continuous, but was broken into two, viz: 160 to 410 kHz and 510 kHz to 30 MHz – thus keeping clear of the 455 kHz intermediate frequency. This was necessary in order to avoid very low impracticable values of local oscillator frequency. From equation (1), if the signal frequency were 455 kHz, for example, then the local oscillator frequency would need to be zero (using the minus case), and this would not be practicable.

Estimates of signal field strengths of the various transmission stations of interest were obtained, together with limiting values of the voltages expected to be induced in the loop antenna by these stations (Ukem, 1983), and are presented in Table 1.

Table 1: Summary of component design values

Component	Value	Quantity
Transistor (2N2222A)	-	3
Resistor	100Ω	3
Resistor	18kΩ	3
Resistor	1kΩ	3
Resistor	2kΩ	3
Capacitor	0.015 μF	3
Capacitor	0.008 μF	3
Capacitor	1000 pF	3
Capacitor	31 pF	1
Antenna Coupling Capacitor	0.008 μF	1
Antenna Coupling Capacitor	0.025 μF	1

The adaptation of the communications receiver was achieved through the modification of some sections to get it to operate at VLF. The modifications were:-

(i) In the RF stages, the RF amplifier of the receiver was bypassed and replaced. The substitute amplifier was transistor-based, rather than vacuum-tube based. The complete RF amplifier circuit – three stages – is given in Fig.2. It was built on a piece of Vero board, all necessary precautions being taken to avoid stray capacitances and dry joints. Measurements taken (but not shown here) after the complete assembly of the amplifier showed the 3dB bandwidth to be 33 kHz (from 2 kHz to 35 kHz), with the maximum voltage gain occurring at 10 kHz.

(ii) The coupling of the antenna to the input of the RF amplifier was modified. In the original circuit of the receiver, the coupling circuits and the RF amplifier stages were designed and tuned to frequencies in the LF, MF, and HF bands. These circuits could not be expected to function efficiently at VLF.

(iii) The third modification was in the local oscillator circuit of the heterodyne stage. This had originally been designed for frequencies that would be mixed with LF, MF, and HF to produce a fixed intermediate frequency. Since the RF stage of the receiver was modified to work in the VLF range, the local oscillator (LO) also had to be altered, in order to maintain the original Intermediate Frequency (IF) and thus minimize overall modifications. To accomplish this, an external signal generator was used to serve as a local oscillator. This was considered a time-saving, cost-reducing measure when compared to designing and building a new IF amplifier.

3.1 Design

The substitute RF amplifier was designed around a general-purpose silicon NPN transistor – 2N2222A. A single stage of the amplifier circuit is shown in Fig. 1.

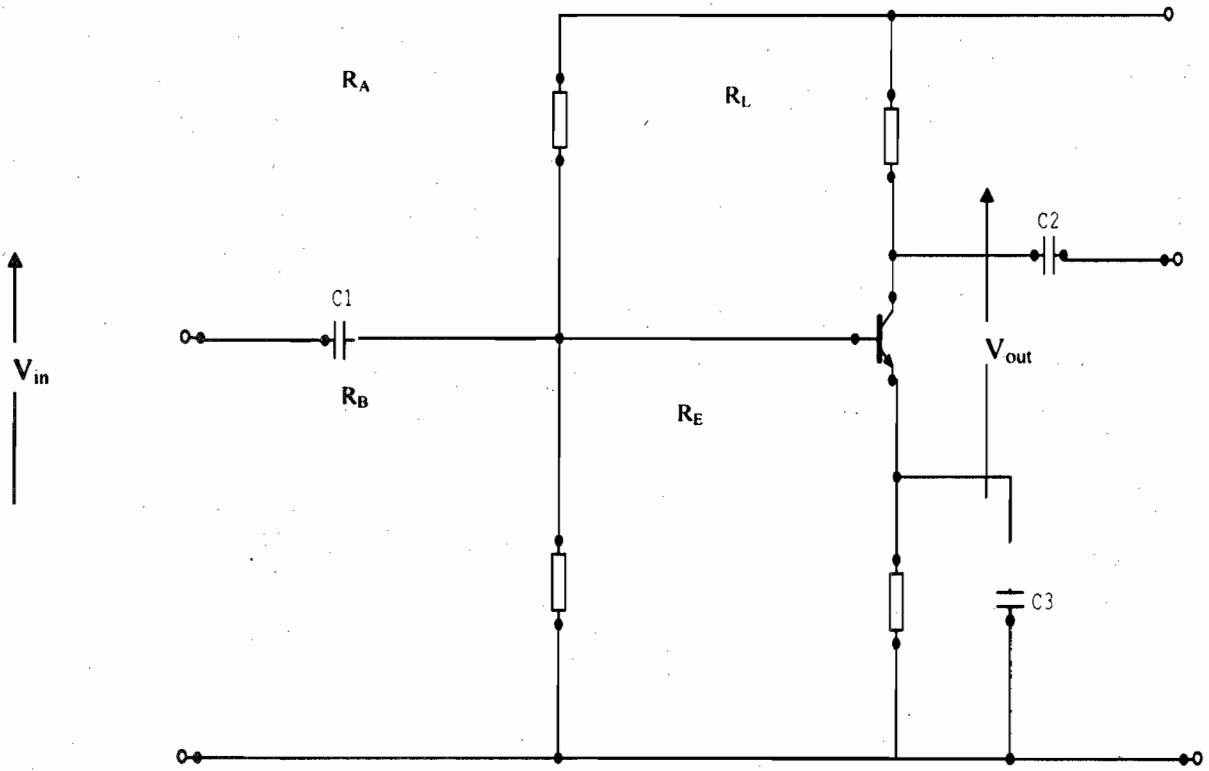


Fig. 1: Single stage of RF amplifier

Q1 NPN

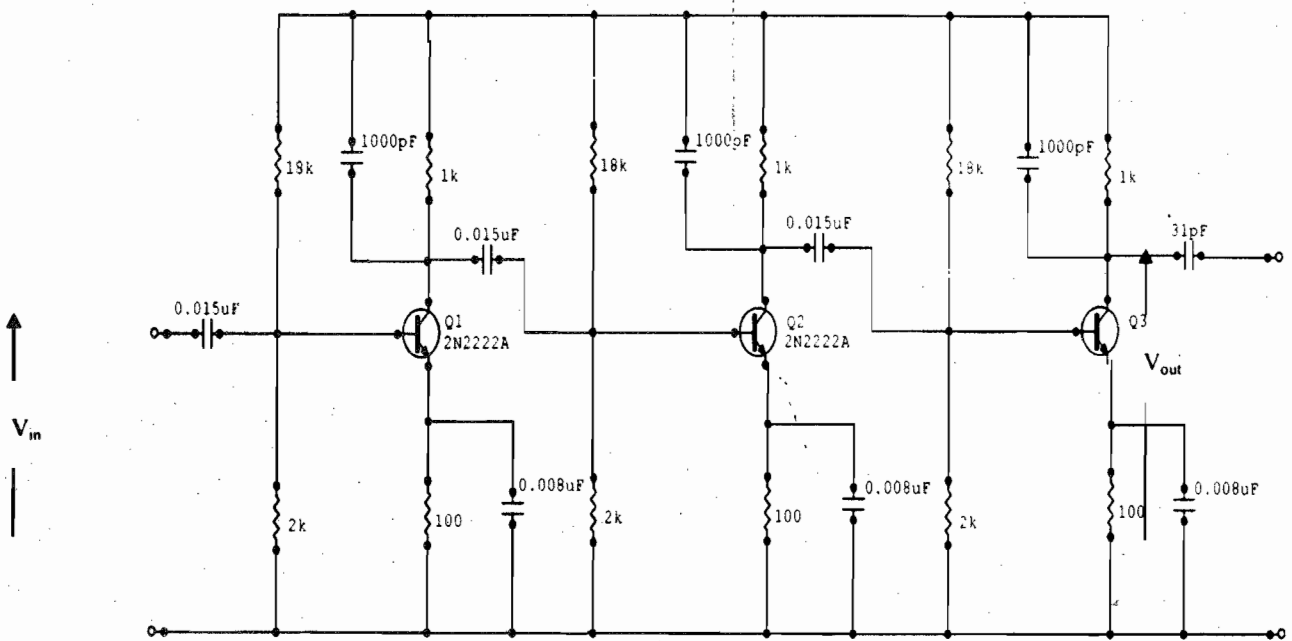


Fig.2: Complete transistorized RF amplifier

From the transistor characteristics (Radiospares, 1983), $V_{CE0} = 40V$, $V_{BE \text{ min}} = 0.5V$, $P_{\text{tot}} = 500 \text{ mW}$, and $h_{fe} = 100$.

Letting $V_{cc} = 20V$ (since $V_{cc} < V_{CE0}$), then

$$\begin{aligned} I_{C \text{ max}} &= P_{\text{tot}} / V_{cc} & (2) \\ &= (500 \times 10^{-3}) / 20 \text{ Amps} \\ &= 25 \text{ mA} \end{aligned}$$

Selecting the operating point current in the load as $I_{CQ} = 10 \text{ mA}$ ($I_{CQ} < I_{C \text{ max}}$), and letting the load resistance R_L drop $\frac{1}{2}V_{cc}$ at the operating point, then from the standard relationship $V = IR$, we have

$$\begin{aligned} R_L &= \frac{1}{2}V_{cc} / I_{CQ} & (3) \\ &= 10 / (10 \times 10^{-3}) \text{ ohms} \\ &= 1 \text{ k}\Omega \end{aligned}$$

The base current, I_{BQ} , at the operating point is

$$\begin{aligned} I_{BQ} &= I_{CQ} / h_{fe} \\ \text{i.e. } I_{BQ} &= (10 \times 10^{-3}) / 100 \quad (\text{since } h_{fe} = 100). \\ &= 100 \mu\text{A} & (4) \end{aligned}$$

$$\begin{aligned} \text{Letting } R_E &= R_L / 10 & (5) \\ &= 10^3 / 10 \text{ ohms} \\ &= 100 \Omega \end{aligned}$$

The voltage V_E is given by

$$\begin{aligned} V_E &= I_E R_E \\ &= 10 \times 10^{-3} \times 100 \quad (\text{since } I_E \text{ is approximately equal to } I_C) \\ &= 1 \text{ V} \end{aligned}$$

$V_{BE \text{ min}}$ for silicon is 0.5 V; consequently, with the emitter voltage at 1 V, the base voltage V_{BQ} has to be at least 1.5 V for conduction. Letting $V_{BQ} = 2 \text{ V}$, the base resistance R_B is calculated to be

$$R_B = 20 R_E = 20 \times 100 \text{ ohms} = 2 \text{ k}\Omega$$

R_A and R_B form a potential divider for the supply voltage V_{cc} . At no-load, the voltage drop across R_B is 2 V. Therefore, the remaining 18 V appears across R_A . From this it follows that

$$20 / (R_A + R_B) = 2 / R_B \quad (6)$$

$$\text{i.e. } 2 (R_A + R_B) = 20 R_B$$

$$\text{and } R_A = 9 R_B \quad (7)$$

Since $R_B = 2 \text{ k}\Omega$, then

$$R_A = 9 \times 2 = 18 \text{ k}\Omega$$

C_1 and C_2 are determined from the desired lower cut-off frequency of the circuit and the associated impedance in the circuit. The expression for C_1 and C_2 is given by (Ukem, 1983)

$$C_1 \text{ or } C_2 = 1 / (3.2 F R) \quad (8)$$

where F is the lower cut-off frequency (Hz)
and R is the associated resistance (ohms).

Letting $F = 10 \times 10^3 \text{ Hz}$ (since none of the stations of interest has a frequency below 10 kHz), and letting the associated resistance be $R = R_B = 2 \text{ k}\Omega$, then, from equation (8),

$$\begin{aligned} C_1 &= 1 / (3.2 \times 10^4 \times 2 \times 10^3) \text{ Farads} \\ &= 1.5625 \times 10^{-8} \text{ Farads} = 0.015 \mu\text{F} \end{aligned}$$

$$\begin{aligned} \text{and } C_2 &= 1 / (3.2 \times 10^4 \times 2 \times 10^3) \text{ Farads} \\ &= 0.015 \mu\text{F} \end{aligned}$$

In this case $R = R_B$ of the next stage and is the same value as that of the previous stage if identical stages are used. For the final stage, R would be the load. In this case the load is the input impedance of the mixer, which is very large – of the order of $1 \text{ M}\Omega$ (the mixer being a vacuum tube) (Ukem, 1983). Therefore, C_2 for the final stage is

$$\begin{aligned} C_2 &= 1 / (3.2 \times 10^{10}) \text{ Farads} = 31.25 \text{ pF} \\ C_3 &= 1 / (6.2 \times 10^4 \times 10^3 \times 2 \times 10^3) \text{ Farads} \\ &= 1 / (12.4 \times 10^7) \text{ Farads} \\ &= 3.0645 \times 10^{-9} \text{ Farads} \\ &= 0.008 \mu\text{F} \end{aligned}$$

The maximum voltage gain obtained for the amplifier was $V_{\text{out}} / V_{\text{in}} = 60$ ($= 35.56 \text{ dB}$).

Coupling between the antenna and the RF amplifier stage was by means of tapped capacitances (Fig.3). From measurements carried out on the constructed square loop antenna (Ukem, 1983),

$$\text{Inductance, } L, \text{ of antenna} = 16 \text{ mH}$$

$$\text{Quality factor, } Q_r, \text{ of antenna} = 10$$

The dynamic resistance, R_{dy} , of the antenna is given by

$$\begin{aligned} R_{\text{dy}} &= Q\omega L = Q2\pi fL \\ &= 10 \times 2\pi \times f \times 10 \times 10^{-3} = 0.32\pi f \text{ ohms} \end{aligned}$$

For frequencies ranging from 3 to 30 kHz, the dynamic resistance falls between

$$R_{\text{dy}} = 0.32 \times \pi \times 3 \times 10^3 = 3 \text{ k}\Omega$$

$$\text{and } R_{\text{dy}} = 0.32 \times \pi \times 30 \times 10^3 = 30 \text{ k}\Omega$$

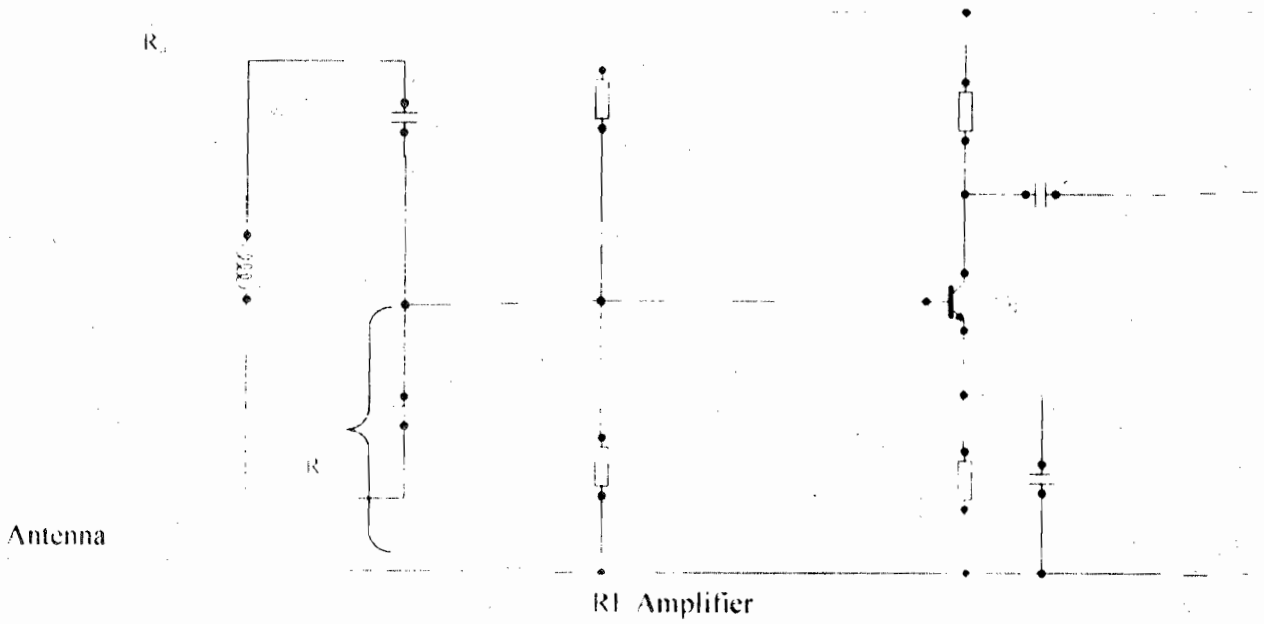


Fig. 3: Tapped capacitance coupling

For convenience the working value of R_{sV} is taken to be = 20 k Ω , since most of the frequencies of interest lie between 10 and 20 kHz. Thus as far as the RF amplifier is concerned, the source impedance is 20 k Ω . Hence (Fig 3)

$$R_{in}' = R_{sV} = 20 \text{ k}\Omega$$

For good matching the condition

$$R_{in}' = (C_2 / C_1)^2 R_{in} \tag{9}$$

needs to be fulfilled

Hence $(C_2 / C_1)^2 = R_{in}' / R_{in} = 20 / 2 = 10$

and $(C_2 / C_1) = (10)^{1/2} = 3.162$

i.e. $C_2 = 3.162 C_1$

Also, the series combination of C_1 and C_2 (Fig.3) should give a resultant capacitance that will resonate with L at the desired frequency. That is

$$C_1 C_2 / (C_1 + C_2) = C_{resonance} \tag{10}$$

Taking the desired frequency as 16 kHz (near the centre of the frequency range of interest), then

$$C_{resonance} = 1 / (4 \pi^2 f^2 L)$$

$$= 1 / (4 \pi^2 \times 16^2 \times 10^6 \times 16 \times 10^{-3})$$

$$= 0.00618 \mu\text{F}$$

Putting this in (Eq.10),

$$C_1 C_2 / (C_1 + C_2) = C_{\text{resonance}} = 0.00618 \mu\text{F}$$

And since $C_2 = 3.162 C_1$

$$C_1 C_2 / (C_1 + C_2) = (3.162 C_1^2) / (4.162 C_1) = 0.00618 \times 10^{-6}$$

From which $C_1 = 0.008 \mu\text{F}$

and $C_2 = 0.025 \mu\text{F}$

A summary of component design values is given in Table 2.

Table 2: Estimated signal field strengths and antenna voltages of LF and VLF stations at Zaria (Ukem, 1983)

			E_{min} ($\mu\text{V/m}$)	E_{max} ($\mu\text{V/m}$)	V_{min} (μV)	V_{max} (μV)
Omega Ω /N	Alda Norway	10.2, 11½, 13.6	0.24	146	0.007	4
Omega Ω /L	Monrovia	10.2, 11½, 13.6	50	439	1.4	9
Omega Ω /H	Hawaii	10.2, 11½, 13.6	4.7×10^{-6}	86	0.13	1.8
Omega Ω /HD	N. Dakota	10.2, 11½, 13.6	2×10^{-3}	94	6×10^{-5}	2
Omega Ω /LR	La Reunion	10.2, 11½, 13.6	0.19	142	0.005	3
Omega Ω /A	Argentina	10.2, 11½, 13.6	5×10^{-10}	99	1.4×10^{-4}	2
Omega Ω /T	Trinidad	10.2, 11½, 13.6	0.8	66	0.02	1.4
Omega Ω /J	Japan	10.2, 11½, 13.6	3×10^{-3}	85	8.5×10^{-5}	1.8
DCF 77	Germany	77.5	6×10^{-3}	258	10^{-9}	42
GBR	Rugby, U. K.	16	2.5	468	0.08	15.68
HBG	Switzerland	75	0.01	205	0.001	32.2
JG2AS JJF-2	Japan	40	8.6×10^{-9}	69	7.2×10^{-10}	5.8
MSF	Rugby, U. K.	60	0.01	273	0.001	34.3
NAA	Maine, USA	17.8	0.09	1123	0.003	42
NDT	Japan	17.4	5.5×10^{-5}	162	2×10^{-6}	6
NLK	Jim Greek	18.6	5.5×10^{-4}	907	2.1×10^{-5}	35.3
NPM	Hawaii	23.4	2.3×10^{-7}	777	1.1×10^{-5}	38
NSS	Maryland	21.4	0.01	1014	4.5×10^{-4}	45.4
NWC	Australia	22.3	7×10^{-5}	790	3.3×10^{-6}	37
RBU	Moscow	66.7	3.4×10^{-4}	138	5×10^{-5}	19
RTZ	Irkutsk	50	5×10^{-7}	82.5	5×10^{-8}	8.6
VGC 3	Khabarovsk	25	1.3×10^{-5}	440	0.07	19
VTR 3	Gerky	20.5	0.18	808	9.6×10^{-3}	34.7

3.2 Testing

With the aid of an RF signal generator and a decade type attenuator, an estimate of the sensitivity of the receiving system was made and found to be of the order of 1 μV at the RF amplifier input. The decade type attenuator enabled more accurate determination of the voltage at the input of the RF amplifier, because it was easier to measure the higher voltage

at the input of the attenuator with greater accuracy and then determine its output by considering its setting. The output of the attenuator was the input to the RF amplifier (see Fig. 4) A frequency counter was included to check the signal generator (LO) frequency. This test gave an indication that the receiving system would give appreciable output for inputs of the order of 1 μV at the RF amplifier input.

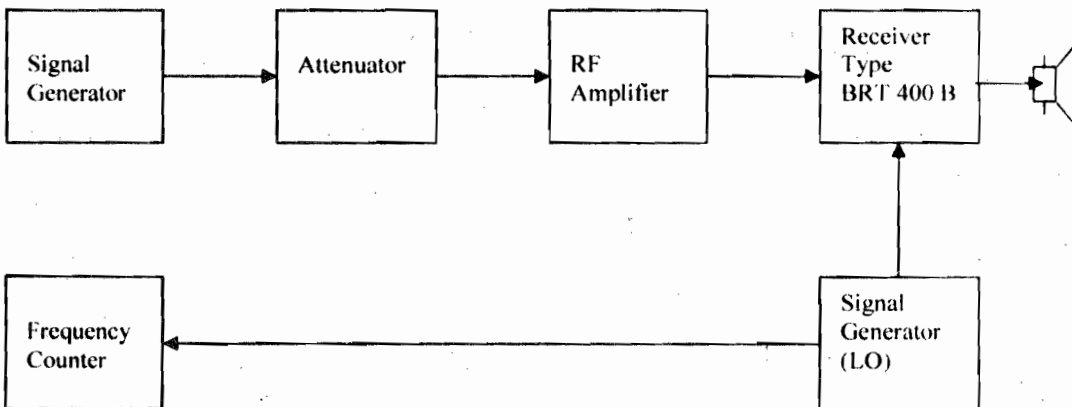


Fig. 4: Estimation of sensitivity

Next, the attenuator was removed and the signal source was connected directly to the RF amplifier, thus feeding signal to the receiver. For both modulated and un-modulated signals, there was output from the receiver as expected. With a modulated signal, the modulating signal tone appeared at the output when the local oscillator frequency was $(455 \pm f_s)$ kHz. With un-modulated signal, the Beat Frequency Oscillator (BFO) in the receiver was used. The BFO frequency was first adjusted to be equal to the IF (455 kHz). Then when un-modulated signal was fed into the receiver, zero-beat occurred at the expected positions of the local oscillator dial of $(455 \pm f_s)$ kHz. These tests were carried out for various values of f_s within the VLF range, and the results were as expected. Thus the receiver was found to be capable of processing the desired signals as a result of the modifications.

Finally the receiver was used to receive actual stations. Stations were detected by searching (through tuning the local oscillator) and obtaining zero-beat. A frequency counter was used to check the local oscillator frequency once zero-beat was obtained. The above tests established that the receiving system, as modified, was capable of receiving some desired signals (Ukem, 2005).

4. RESULTS AND DISCUSSIONS

The overall result of the various modifications carried out on the vacuum-tube communications receiver was that the receiver could finally be used to receive radio signals in the VLF range. The original receiver was designed to operate at LF, MF, and HF, and so could not receive VLF signals. The modification of the RF stage was the major activity that brought about the operational change in the receiver. The new RF stage was able to accommodate VLF, unlike the original circuit. The accompanying local oscillator also was modified, in order to produce the original intermediate frequency of the system. This was a way of reducing the overall needed modifications to the receiver. Maintaining the same intermediate frequency meant that the same (existing) IF amplifier stage could be used, and every circuit beyond this stage needed not to be modified. Among other things, this was also a cost saving strategy. It could have been equally effective to retain the local oscillator and then design the IF stage to work at a new intermediate frequency. This, however, would have been more expensive, more time consuming, and counter productive, since cost saving was part of the objective. Use of transistors for the RF amplifier has advantage over vacuum tubes. The design is easier to realize and also the circuit is easier to use as power supply requirements are easier to meet. Transistors generally consume less power as they do not require heating of elements as do vacuum tubes. Coupling of the stages is also easier with transistors than with vacuum tubes especially, considering stray capacitance, which is more obvious with vacuum tubes than with transistors. Sensitivity of the circuit is also enhanced when transistors are employed.

With the modified receiver, along with other components of the receiving system, some VLF stations were received. The stations received and identified were the GBR station (16 kHz) at Rugby, United Kingdom, the NAA station (17.8 kHz) at Cutler, Maine, U.S.A. and the NLK station (18.6 kHz) at Jim Creek, Washington, U.S.A. Identification of the transmissions was achieved by comparing the tone emitted by the receiver when slightly de-tuned with the published unique signal pattern for each station, in addition to aligning the antenna in accordance with the approximate estimated bearing of the station. The actual values of field strength for each received station were not recorded. This was not considered necessary, as the intension of the work was to establish that such stations could be received at the location. With the estimated values of field strength as shown in Table 2, and with the sensitivity of the receiver known to be $1 \mu\text{V}$, it was only necessary to listen for the expected tone patterns to establish receivability. All the identified stations transmit at

frequencies within the desired range (VLF range). The ranges of antenna voltages expected for these stations, as seen in Table 1, have upper limits well above the sensitivity level ($1 \mu\text{V}$) of the receiver, indicating that these stations should be receivable.

This development meant that frequency and time signals from these stations had become available in the laboratory in this location as a result of this work. The information in these signals was therefore available to be applied in any chosen way, thus opening up vast possibilities. The significance of this outcome is that a receiving system for VLF signals became available in the laboratory. One important area of application for such a receiver, as earlier mentioned, is the reception of standard time and frequency signals. Time and frequency information dissemination services exist in various frequency bands, including VLF. This, then, meant that frequency and time signals from these stations could be available in the laboratory in this particular location as a result of this work. The information in these signals would therefore be available to be applied in any chosen way.

5. CONCLUSION

From the results of the investigation, it is concluded that some signals in the Very Low Frequency range can be received with a simple receiver system that includes an air-cored loop antenna and a modified communications receiver. The significance of this is that valuable information, including information on standard time and frequency, can be extracted with relatively inexpensive equipment. This opens up opportunities for the application of these signals in the locality, especially by students desiring to experiment with and explore standard time and frequency. The absence of sophisticated equipment due to high cost need not, therefore, be a total barrier to the advancement of knowledge in this field. Application in such areas as the calibration of measuring instruments, tuning of musical instruments, and synchronization of consumer electronic products also becomes more feasible.

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