Vintage Radio

By Dr Hugo Holden

Made in New Zealand: the Pacemaker transistor radio

. . . plus a look at mixers, RF stages & image rejection

A vital part of any AM superhet transistor radio is the mixer or mixer-oscillator and this month we take a look at how these circuits work. We also describe the New Zealand-made Pacemaker Transportable radio and compare its main features with the Sony TR-72 described last month.

THE NZ-MADE Pacemaker is credited as being one of the world's first commercial transistor radios to have a tuned RF amplifier stage. In fact, it may well have been the very first.

Most transistor radios of the mid 1950s (for example the 1954 Regency TR1 and the 1956 Sony TR-72) did not have an active tuned RF (radio-frequency) front-end. Indeed, most medium-wave (ie, broadcast-band) radios didn't have active RF stages right through into the 1970s. By contrast, shortwave radios often did.

But why was this and what are the advantages of an active tuned RF stage?

Nearly all transistor radios employ an "autodyne" mixer or "converter" circuit. This is a combined mixer-oscillator circuit and is sometimes called an 'additive mixer'. However, this is misleading because the mixing process involves multiplication of the incoming signal with the oscillator signal, not addition.

The fundamental principle of the superheterodyne (or superhet) radio involves frequency conversion. This is done by converting the received signal frequency down to a lower frequency called the 'intermediate frequency' or IF. This is why mixers are sometimes also called 'converters'.

In typical transistor radios, the IF is nominally 455kHz. The following IF amplifier stage is usually composed of two transistors and three IF transformers but some radios, such as the Pacemaker, only have one IF transistor and two IF transformers.

Most of a transistor radio's signal gain and selectivity is in the IF amplifier. While the IF transformers are tuned to a centre frequency of 455kHz, their bandwidth is still wide enough to pass audio frequencies through to the detector. This bandwidth is typically between ±3kHz and ±5kHz.

The preceding converter stage usually takes one of two forms: either a mixer transistor with a separate oscillator transistor feeding it or, more commonly, a single-transistor oscillator which also acts as a mixer. The latter is commonly referred to as a 'mixer-oscillator'.

When the received (ie, tuned) signal is 'mixed' with the oscillator signal, sum and difference components of the two signal frequencies appear in the mixer's output. So if a received signal frequency of 650kHz is mixed with an oscillator signal frequency of 1105kHz, the sum and difference frequencies will be 1755kHz and 455kHz respectively. However, only the 455kHz signal passes through the IF amplifier due to the IF transformer tuning.

Fig.1 shows the basic configuration of a superhet receiver and gives some example frequencies. In operation, the oscillator frequency is set so that it always runs 455kHz (ie, the IF) higher than the incoming tuned signal frequency. That's done by simultaneously tuning the antenna circuit and the oscillator using a 2-gang variable capacitor, so that the oscillator signal tracks 455kHz above the received frequencies.

Of course, this tracking is never absolutely perfect and there are tracking errors. However, with good design, these errors are virtually zero at the extremities of the band and in the centre.

As shown on Fig.1, there is another frequency known as the 'image frequency' that could also be accepted by the IF stage. This image frequency (or potential interfering radio station) will have a lower signal level than the wanted signal because the antenna coil is tuned to the wanted signal. However, if the image frequency signal is strong enough, it could break through.

As stated, the IF amplifier passes only 455kHz signals and rejects all other signals. The problem is that the "image" frequency is 2 x 455kHz = 910kHz above the tuned frequency, or 455kHz above the oscillator. As a result, the mixer/oscillator also converts it to 455kHz (ie, the difference product) and so it is at risk of breaking through.

Fortunately, image frequencies above 790kHz are outside the AM broadcast (MW) band and there are few (if any) stations transmitting in the region from 1700-2500kHz to cause image problems. However, that's not the case on the shortwave bands where it's not uncommon for another station to be transmitting 910kHz above the tuned frequency.

One solution to the image problem is to have a tuned "preselector" or RF stage consisting of an extra transistor and tuned circuit prior to the mixer. This stage helps to boost the wanted frequency and attenuate other frequencies further away (such as the image frequency).

Basically, it improves the selectivity and provides additional gain to improve sensitivity (ie, to boost low-signal reception). It also increases the signal level fed to the mixer, potentially helping to lower the noise generated in the mixer itself. This is the design approach in the Pacemaker radio.

How the mixer works

The mixer/oscillator stage is usually based on just a single transistor but it performs an extraordinarily complex role. Just how a mixer stage works is often glossed over in many texts. However, its function is critical in even the most basic AM transistor radio.

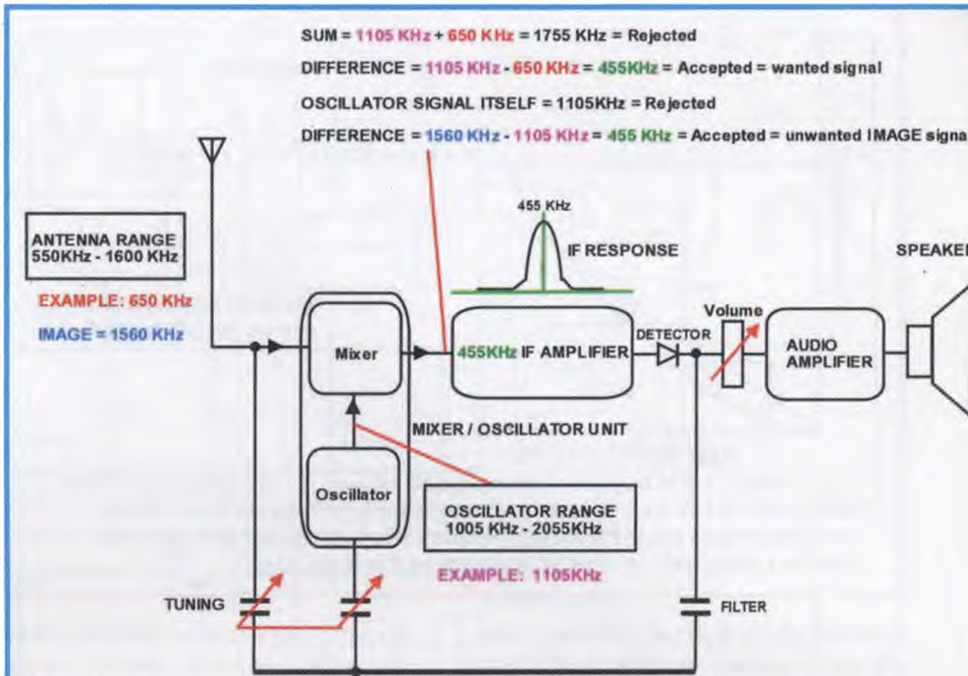


Fig.1: the basic configuration of a superheterodyne AM radio receiver. Also shown are the various frequencies generated by the oscillator/mixer circuit when the set is tuned to 650kHz. Note that the oscillator is tuned so that it always runs 455kHz higher than the tuned signal frequency.

In order to generate sum and difference frequencies of two periodic waveforms such as sinewaves (or cosine waves), the two signals must in fact be multiplied together. It won't work if the signals are simply added.

So how does a transistor mixer-oscillator stage multiply two signals? First, let's consider two cosine waves with angular frequencies of ***w1*** and ***w2*** radians per second (note $w = 2\pi f$, where f is the frequency). Multiplying the angular frequency w by time t yields the angle in radians. Thus, the electrical or magnetic component of a radio wave has the general form $Y = A.\cos(wt)$ where Y is the amplitude varying with time and A is the peak amplitude, while the frequency $f = w \div 2\pi$.

If we multiply the two normalised angular components together, we get: $\cos(w1t).\cos(w2t) = 0.5\cos[(w1 + w2)t] + 0.5\cos[(w1 - w2)t]$

This trigonometric identity is available from many texts. So something quite remarkable has happened. Multiplying the two waveforms has resulted in two other components which are (1) the sum of the two initial frequencies and (2) the difference of the two frequencies. They both have half the amplitude of the original waveforms.

Note: this result is also recognisable as the frequency spectrum of amplitude modulation (AM) itself, with a central carrier and a sideband on either side with half the amplitude. Mixers are in fact also modulators.

In specialised mixer integrated circuits (such as the MC1496), the multiplication of two signals is exactly as per the equation above. This IC is a "voltage multiplier". However, in the case of a single transistor mixer (or mixer-oscillator) in a typical transistor radio, the situation is a little different.

Fig.2 shows what happens when two different signals, a and b, are added and then amplified either by a linear amplifier in one example or a "square law" amplifier in the other. As can be seen, linear amplification results in simple scaled up amplitudes of signals a and b. On the other hand, if the amplification obeys a square law, then the product of signals a and b appears as the term $2ab$.

In the latter case, signals a and b have been multiplied by summation followed by square law amplification. Other signals also appear which are equal to the square of signal a and the

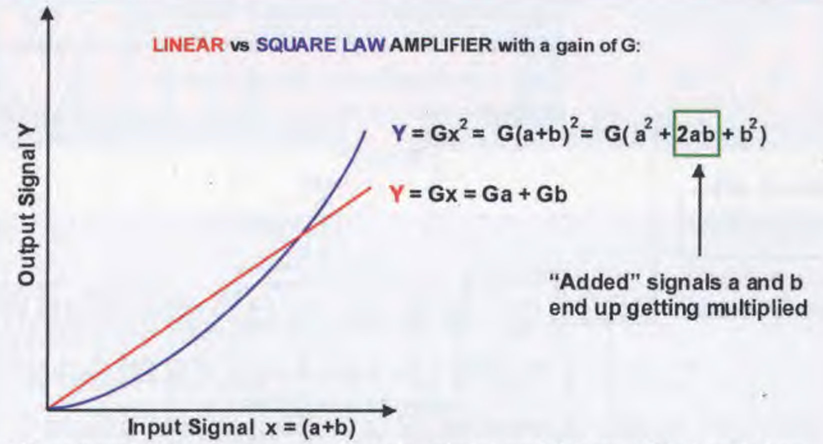


Fig.2: here's what happens when signals 'a' and 'b' are added and then amplified either by a linear (red) amplifier or a "square law" (blue) amplifier. Note that if the amplification obeys a square law, then the product of signals 'a' and 'b' appears as the term "2ab".

square of signal ***b***. If we represent these signals as cosine waveforms instead, we find out what happens when two added waveforms are squared:

$(a + b)^2 = [\cos(w1t) + \cos(w2t)]^2$

$= 1 + 0.5\cos(2w1t) + 0.5\cos(2w2t) + \cos[(w1 + w2)t] + \cos[(w1 - w2)t]$

Again the sum and difference of the two waveforms has appeared but this time their amplitude hasn't halved. The "1" represents a DC component. In addition, there are components which are twice the frequency (ie, second harmonics) of the original cosine waveforms.

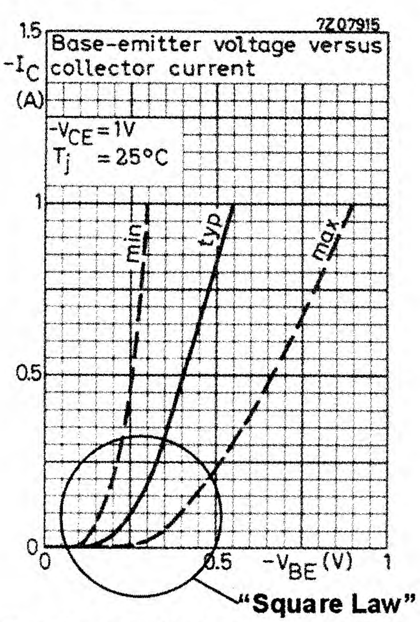


Fig.3: base-emitter voltage versus the collector current for a typical PNP germanium transistor. Note that the lower section of each curve is non-linear and has an approximate 'square law' characteristic.

So squaring a cosine (or sine) wave doubles its frequency and one easy method of frequency doubling is to pass a sinewave through a squarer circuit. As a result, the output of a simple transistor mixer stage consists of a "cocktail" of different signals, as follows:

(1) the received radio station frequency;
(2) the oscillator frequency;
(3) the sum of the oscillator and tuned station frequencies;
(4) the difference between the oscillator and tuned station frequencies;
(5) twice the tuned station frequency;
(6) twice the oscillator frequency; and
(7) the transistor's DC bias.

In addition, for anything other than perfect square law amplification, there will be other frequencies or harmonics in the mixer's output current or output signal. In fact, the transfer curve can be represented by a polynomial of the form: $ax + bx^2 + cx^3 + dx^4 \ldots$ *etc.*

It turns out that "cubing" a sinewave, for example, results in a third harmonic, ie, three times the frequency. This means that there can be second, third, fourth, fifth etc harmonics of both the oscillator signal and the tuned frequency at the mixer's output. However, these signals are rejected by the IF amplifier which only amplifies 455kHz ± about 5kHz.

A transistor operating at a low bias level has a voltage amplification response curve which is non-linear. In fact, it's very similar to the blue curve shown in Fig.2. This isn't obvious from most transistor data sheets because the transistor's base-emitter voltage usually isn't plotted against collector current.

Instead, more often than not, the base current is plotted against collector current which looks more linear and the slope at any point is the small signal current gain.

A transistor's base-emitter junction has a response (or function) that's very similar to a simple diode. The collector current is converted to a voltage by the impedance in the collector load circuit. So a transistor operating at low bias levels, is an approximate square law device when used as a voltage amplifier.

So too are field effect transistors and an MPF102 junction FET, for example, also makes a good mixer or mixer/oscillator (and these better approximate a square law function).

Fig.3 (from a Philips manual) shows the base-emitter voltage versus the

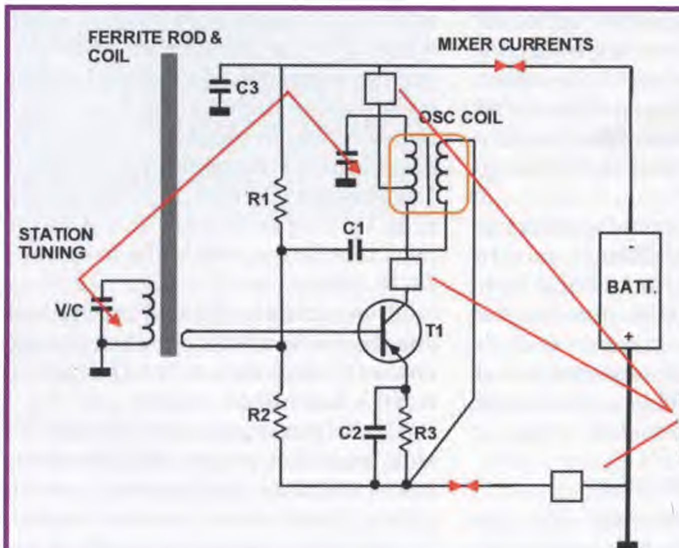


Fig.4: a typical 1-transistor self-oscillating mixer stage. This is similar to the one used in the Sony TR-72 and is often referred to as an 'autodyne converter'.

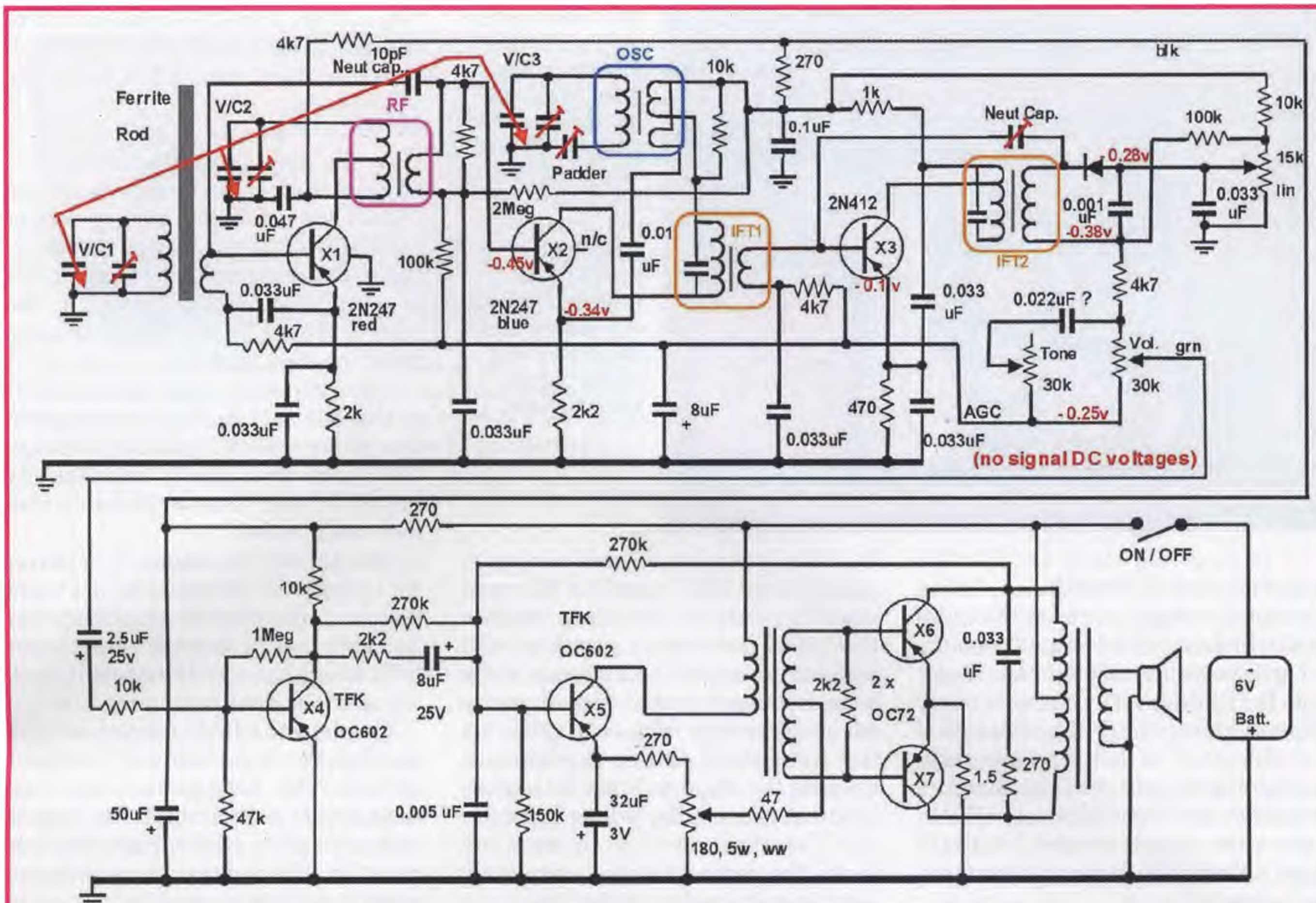


Fig.5: the circuit of the NZ-made Pacemaker transistor radio. It uses seven PNP transistors, with X1 functioning as an RF amplifier. X2 is the mixer/oscillator, X3 the IF amplifier and X4-X5 form the audio amplifier stage.

collector current for a PNP germanium transistor. As can be seen, the lower section of each curve is non-linear and has a square law characteristic, especially for base-emitter voltages of less than 0.5V.

Typical mixer

Fig.4 shows a typical one-transistor self-oscillating mixer stage. This is the basic configuration used in the Sony TR-72 (except that the TR-72 uses an NPN transistor) and is often referred to as an 'autodyne converter'. The mixer in the Pacemaker radio described later has a slightly different configuration.

The mixer's output, containing all the signal components, is fed to the primary of the first IF transformer. As with the other IF transformers in the radio, this is tuned to a centre frequency of 455kHz.

The first IF transformer's primary winding is simply placed in series with the mixer circuit's output. It's in series with mixer transistor's emitter in the TR-72 and in series with the collector in the Pacemaker radio.

There are many other single-transistor self-oscillating mixer configurations. Often, the feedback that's necessary to sustain oscillation is taken from the oscillator coil and applied to the transistor's emitter instead of its base. However, they all have the same function and it's necessary for the transistor to be lightly biased and operating in its non-linear region.

The variable capacitor (V/C) tunes the ferrite rod antenna circuit and is ganged to a second variable capacitor which tunes the oscillator coil. In most transistor radios (eg, the Sony TR-72), the tuning-gang section used in the oscillator is smaller that the antenna section. This is done to ensure that the oscillator frequency tracks the tuned frequency, so that they remain close to 455kHz apart with minimal tracking errors.

In some radios (such as the Pacemaker) though, the tuning gang sections are identical. As a result, an extra capacitor, called a 'padder', is placed in series with the oscillator section to reduce its value by the correct amount.

Referring back to Fig.4, R1 and R2 are the transistor's bias resistors and these set its DC operating conditions. The tuned RF signal from the small coupling coil on the ferrite rod is fed to the transistor's base circuit, while the oscillator feedback signal is fed to the base via C1 (which helps maintain oscillation).

Note that the coupling coil on the ferrite rod has a relatively small number of turns feeding the transistor's base circuit. This ensures that the main tuned winding on the ferrite rod is not heavily loaded. Capacitor C2 and resistor R3 help the transistor maintain a stable DC bias condition.

Finally, the polarity of the oscillator coil windings is such that the feedback is positive to sustain oscillation. Capacitor C3 bypasses any radio frequencies on the supply line.

Pacemaker circuit details

I was unable to locate the original

The view inside the Pacemaker Transportable. Most of the parts are obscured by its large metal chassis although the ferrite rod antenna is visible, as are the 3-gang tuning capacitor, the battery and the driver and audio output transformers.

manufacturer's schematic, so it was laboriously traced out from the radio itself which is probably a 1960 version.

Fig.5 shows the circuit details. Apart from the RF stage, it's similar in many respects to Sony's TR-72 but one obvious difference is that the Pacemaker Transportable uses PNP germanium transistors while the TR-72 uses NPNs. It also uses one less transistor in the IF stage, although both are still 7-transistor radios.

The RF stage (or pre-selector) is based on transistor X1 (a 2N247), an RF coil and one gang of the 3-gang tuning capacitor. This RF stage is neutralised using a fixed 10pF capacitor to ensure stability. This is necessary because the tuned circuits in the base and collector sections of X1 operate at the same frequency and would otherwise exchange energy with each other via the transistor's Miller capacitance, causing the stage to burst into oscillation. As stated, the tuning capacitor (V/C) has three identical sections and looks the same as those commonly used in valve radios of the time.

The mixer-oscillator stage is based on transistor X2. This has in-phase feedback from the oscillator coil to its emitter in order to sustain oscillation. This differs from the mixer circuit of the Sony TR-72 which uses out-of-phase feedback to the transistor's base.

IF amplifier

As mentioned, the Pacemaker has one less IF amplifier stage and one less IF transformer than typical transistor radios of the time. However, the resulting loss of gain and selectivity in the IF section is compensated for by the gain provided by the tuned RF stage based on transistor X1.

In fact, the net overall gain is similar to that in a standard radio. However, due to the selectivity of the RF stage, the image rejection is substantially improved and there is probably also less mixer noise.

The 455kHz IF signal from mixer X2 is fed to IF transformer IFT1 and then to neutralised IF amplifier stage X3. This in turn feeds IF transformer IFT2 which then feeds the resulting IF signal to the detector diode.

The detector diode carried no type number but is probably an OA90 or similar. The detector has been arranged with bias control. The diode's cathode is at the AGC voltage, which is about -0.38V, and this tends to excessively forward bias the diode, even in the absence of signal. To counter this, another negative voltage (developed across a 15kΩ trimpot) is applied to the anode.

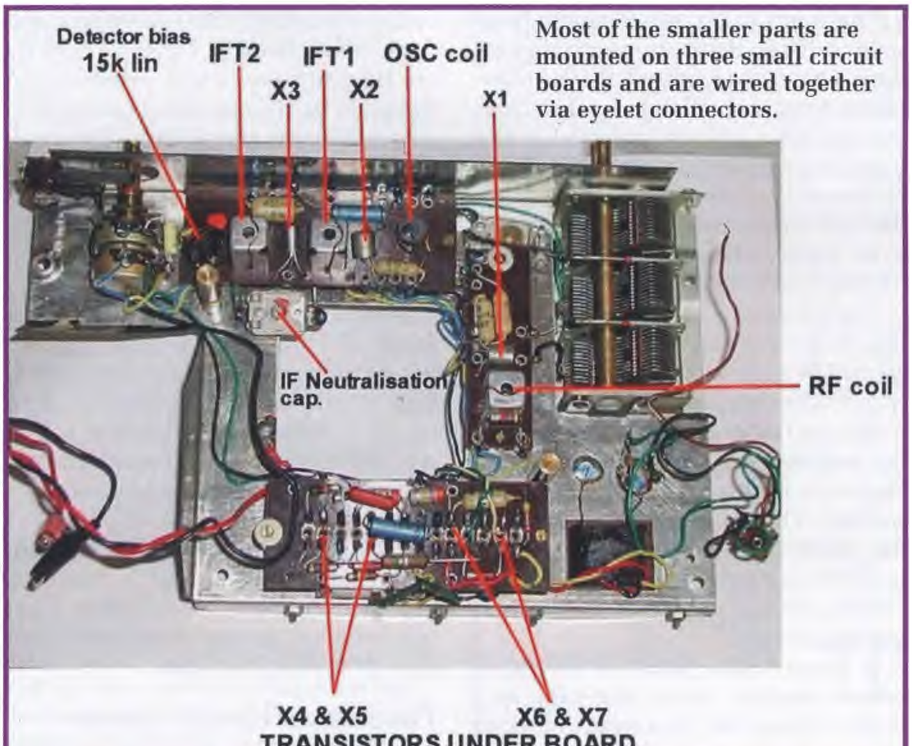
In my set, this was about -0.28V, which leaves a residual 100mV of forward bias. This value was probably the factory setting, since a small amount of detector forward bias can help demodulate weak signals.

Automatic gain control

AGC is applied to transistors X1, X2 and X3. Note that less AGC range is applied to mixer-oscillator X2, as it is sourced from a divider comprising 100kΩ and 2MΩ resistors. High AGC levels can deactivate an oscillator and some so designers consider it unwise to apply AGC to this stage. In this circuit though, the 2MΩ resistor biases X2 so that it stays in oscillation even though some AGC is applied.

Audio amplifier stages

The audio amplifier also has some interesting features. Input stage X4 is a grounded-emitter amplifier and is DC stabilised by collector-to-base feedback via a 1MΩ resistor. Direct coupling from X4's collector is then



Most of the smaller parts are mounted on three small circuit boards and are wired together via eyelet connectors.

The Pacemaker Transportable is housed in an attractive timber case with the on/off/volume and tuning controls mounted at the top. Note that the tuning dial has 'North Is' and 'South Is' sections and carries NZ station call-signs.

used to establish the bias on driver stage X5. X5's emitter current in turn sets the bias current for output transistors X6 & X7 (both OC72s), depending on the voltage developed across a 180Ω 5W wirewound adjustable resistor.

This arrangement is very unusual. It means that the output stage's bias and current stability is controlled by input transistor X4's Vbe (base-emitter voltage) characteristic, which is very dependent on temperature. As it heats up, X4's Vbe drops and the transistor turns on harder. This lowers the voltage on X4's collector and in turn lowers the base bias voltage applied to X5.

As a result, X5's emitter voltage drops and this tends to 'throttle back' the output transistors. So it would appear the designers have used audio input transistor X4 as a "temperature compensation device" for the output stage.

There is also a small amount of low-frequency and negative DC feedback from the collector of X6 (ie, via the 270kΩ resistor). This contributes to the DC stability but this effect is limited due to the relatively low resistance of the output transformer's primary windings. It could also possibly be some sort of anti motor-boating network, as its AC frequency response is such that it's only active below about 100-200Hz.

Once again, this arrangement is very unusual. There is no conventional audio AC negative feedback in the Pacemaker, such as seen around the audio stages of radios such as the Sony TR-72. Normally, feedback is derived from the speaker itself and fed to the driver transistor's emitter circuit.

Assembly method

One of the accompanying photos shows the view inside this unique radio. There's really little to see since most of the parts are covered by a metal chassis and are protected from the owner's prying fingers. However, the ferrite rod assembly and the audio driver and output transformers are visible, along with the elliptical Rola loudspeaker and the 3-gang variable tuning capacitor.

The radio runs from a 6V lantern battery (also visible). This is extremely long-lasting in this application since the current drain is only about 10mA.

Another photo shows the chassis assembly after it has been removed from the cabinet. Most of the smaller parts are mounted on small boards and are wired via eyelet connectors.

Finally, as with the Sony TR-72, the Pacemaker Transportable is housed in an attractive timber case with the controls mounted at the top. It also has a metal carrying handle. All in all, it is a well-made radio with excellent performance. **SC**