A phase-locked loop f.m. tuner

Novel voltage-controlled oscillator in p.l.l gives good linearity.

by J. L. Linsley Hood.

The major problem in the design of a high quality f.m. receiver, as distinct from an a.m. system operating in the same frequency band, is the inherent non-linearity of the frequency/ voltage characteristics of most f.m. demodulator techniques.

This non-linearity arises in part from the method of operation of the demodulator circuit itself, and partly from the fact that all f.m. demodulators are affected, to some extent, by the magnitude of the input signal, in that an increase in the magnitude of the input signal will generally result in an increase in the demodulator output. This leads to the result that if the i.f. or r.f. amplifier stages preceding the demodulator have a "peaky" characteristic, so that their output magnitude varies as a function of input signal frequency, this peakiness of response will be superimposed on the transfer curve of the demodulator, giving a resulting frequency/ voltage characteristic which is very irregular.

Although the normal f.m. demodulator non-linearities will generally be of a type which leads to low-order harmonic distortion (2nd or 3rd harmonic, depending on the shape of the transfer curve) peakiness in the r.f. or i.f. tuned circuits, due to mistuning or incipient instability, can lead to complex high-order harmonic distortion components which may be very objectionable to the listener.

This problem can be made much less troublesome by the use of an effective voltage limiter circuit prior to the demodulator. This will also be beneficial in eliminating impulse type interference, fading, and amplitude variation from station to station. However, this technique leads to the further problem that an increase in r.f. or i.f. gain is required for proper operation, which tends to bring up inter-station noise to the same a.f. output level as that of a fully modulated carrier. This can be very irritating in practice, and consequently most commercial f.m. receivers incorporate post-demodulator muting circuits to suppress inter-station noise, in spite of the fact that most of the available muting systems introduce some additional harmonic distortion.

There is, however, one f.m. demodulator system which offers an almost complete solution to the problem of non-linearity, and also offers a considerable reduction in the subsequent irritation of inter-station noise, and this is the phase-locked-loop (p.l.l.) technique. Moreover, the p.l.l. demodulator technique can also offer improvements in the on-station signal-to-noise ratio and capture sensitivity, and adjacent-channel selectivity, together with the possibility of a receiver which requires no tuned circuits in the i.f. demodulator or decoder sections.

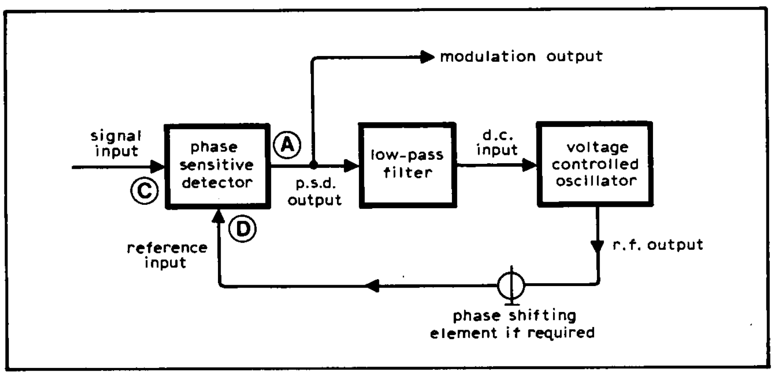


Fig. 1. Block diagram of an elemental phase-locked loop. The phase shifter is required when the circuit is used for stereo decoding.

The basic p.l.l.

The circuit is essentially a closed-loop servo-system built up from three components; a phase sensitive detector (subsequently referred to as a p.s.d.), a voltage-controlled oscillator (the v.c.o.), and a low-pass filter, connected together in the manner shown in Fig. 1. The intention is that when the system is "in lock" the oscillator shall be held in frequency and phase synchronism with the incoming signal.

If we define a phase-sensitive detector as a device which can give an instantaneous direct-voltage output which is related to the phase angle between two separate inputs—C and D in Fig. 1—such that the output has, for example, a positive voltage output when the two inputs are in phase, a negative output polarity when the two inputs are in phase opposition, and zero output when the two inputs are at quadrature ($\pm 90°$), it can be seen that if the two inputs are at different frequencies, then the output from the p.s.d. will be an alternating voltage having a periodicity which is equal to the difference frequency between the two input signals. This arises because with two dissimilar input frequencies the signals will be in-phase, at quadrature, and in antiphase sequentially in time.

The voltage-controlled oscillator gives an output at a frequency which is (instantaneously) a function of its direct input (control) voltage. When the input frequency at C varies so that it approaches the free running frequency of the v.c.o., the voltage fed to the v.c.o. from the p.s.d. (point A) will cause the v.c.o. to increase or decrease in frequency in such a manner as to bring it into phase synchronism with the input signal. In this condition the phase-locked loop is said to be "in lock".

Then, so long as "lock" is held, if the input signal frequency at C varies, the output voltage from the p.s.d. will also vary in such a way as to keep the v.c.o. running in synchronism with the signal input, unless the frequency excursions are such that the v.c.o. input requirement exceeds the output voltage capability of the p.s.d. or the subsequent filter, in which case the lock will be lost. However, while the loop remains in lock it is clear that the control voltage applied to the v.c.o. has a relationship to the input signal at C which is as linear as the v.c.o. voltage/frequency characteristics permit. Moreover, if the input signal is modulated in frequency, the p.s.d. output voltage will be a replica of the modulating signal.

Among other functions, then, a phase-locked loop can be a very linear f.m. demodulator. The selectivity and noise bandwidth of this system then depend on the low-pass filter characteristics, together with any subsequent filtering of the demodulated signal.

Ideally, if the p.s.d. output is only a function of the frequency difference between the two input signals, the system will also give a high degree of amplitude modulation rejection. Since most practical p.s.ds are somewhat less than perfect in this respect, it is advisable to interpose some amplitude limiting circuit in the signal path prior to the p.s.d.

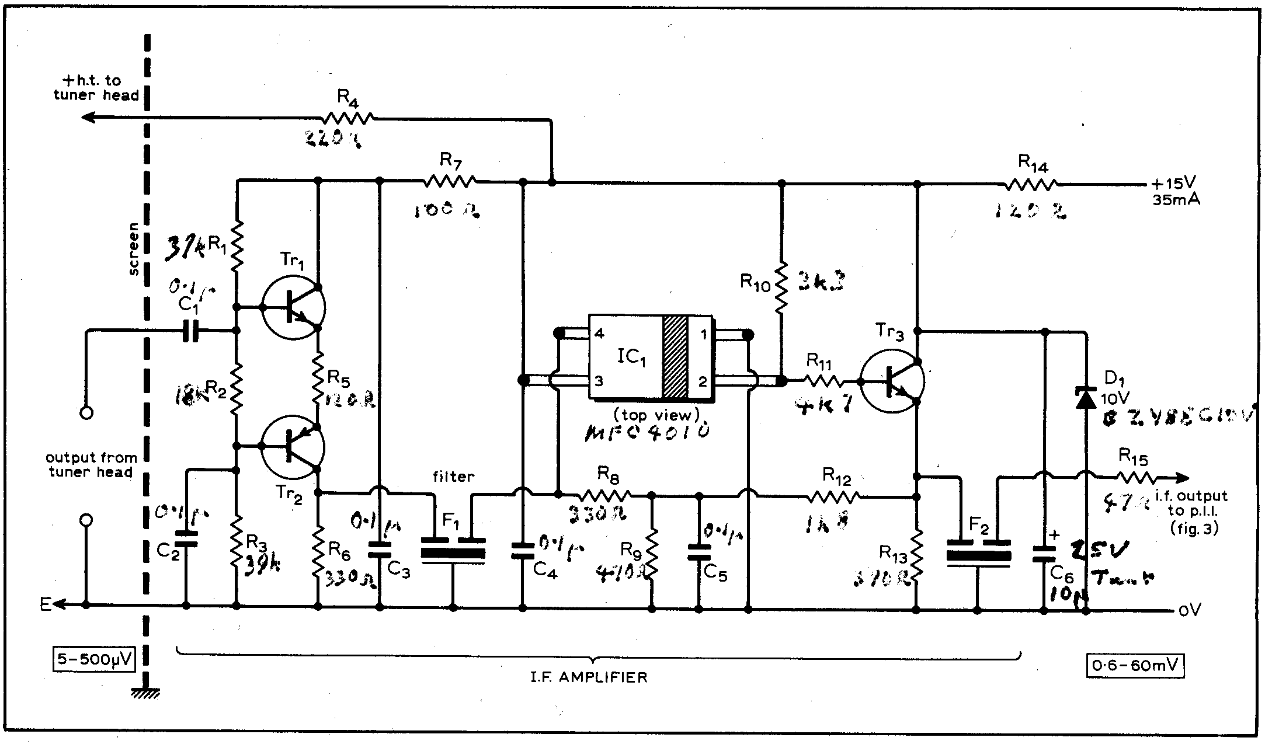
Practical elements. Although there are now a number of commercially available integrated circuit p.l.l. systems suitable for f.m. demodulation—available from Signetics, National Semiconductor, Harris and other manufacturers—these tend as yet to be rather expensive. Also, of those tested, the claimed and measured frequency/voltage transfer linearity was rather poorer than the desired figure of less than 0.1% non-linearity for ±75 kHz deviation at 10.7 MHz. An attempt was therefore made, as a starting point, to develop a voltage or current controlled oscillator system which had a linearity of this order, and this was described in an earlier article.[2] This was then incorporated into the phase-locked loop i.f. system described below, and the results obtained with the several units of this type built so far have been most gratifying.

In order to simplify the design of the complete system a commercially available f.m. tuner 'head' was employed, of which there are several satisfactory alternatives. Because the i.f. strip has a fairly high input impedance, the input matching to the head should be relatively uncritical, and the choice of head unit to be employed is left to the constructor.

Circuit design i.f. strip. Since I live in a fringe area, in which reception is complicated by the proximity of several ranges of high hills, so that the most satisfactory BBC transmitter is located some 65–70 miles distant, and since the only currently available stereo signals originate at distances of 90–130 miles, high sensitivity was a major requirement for this design, and an input i.f. sensitivity, for reliable lock, of five microvolts was required.

The preliminary i.f. amplification is obtained by the circuit shown in Fig. 2. In this the input interface between the tuner head and the i.f. strip consists of a complementary cascode circuit[1] employing the two

Fig. 2. The i.f. amplifier provides a gain of about 120.



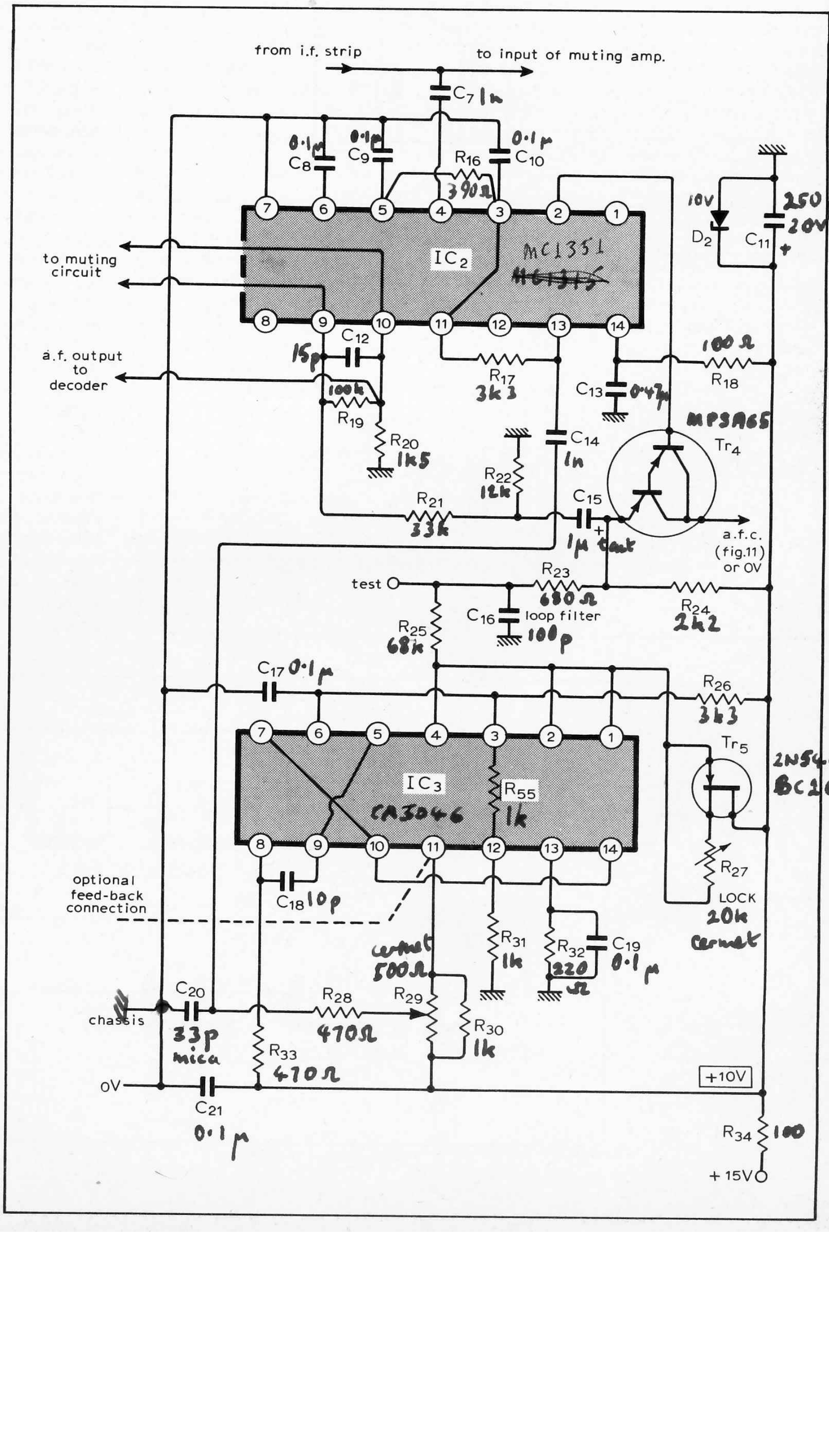
transistors Tr_1 and Tr_2. This achieves the necessary impedance transformation between the output of the head and the 330-ohm drive impedance required by the ceramic filter, Vernitron type FM4, with stability and no loss of gain. A simple emitter follower cannot be used in this application, unfortunately, because at these frequencies the base-emitter capacitance converts any such system having a tuned circuit in base and emitter circuits into a form of Colpitts oscillator.

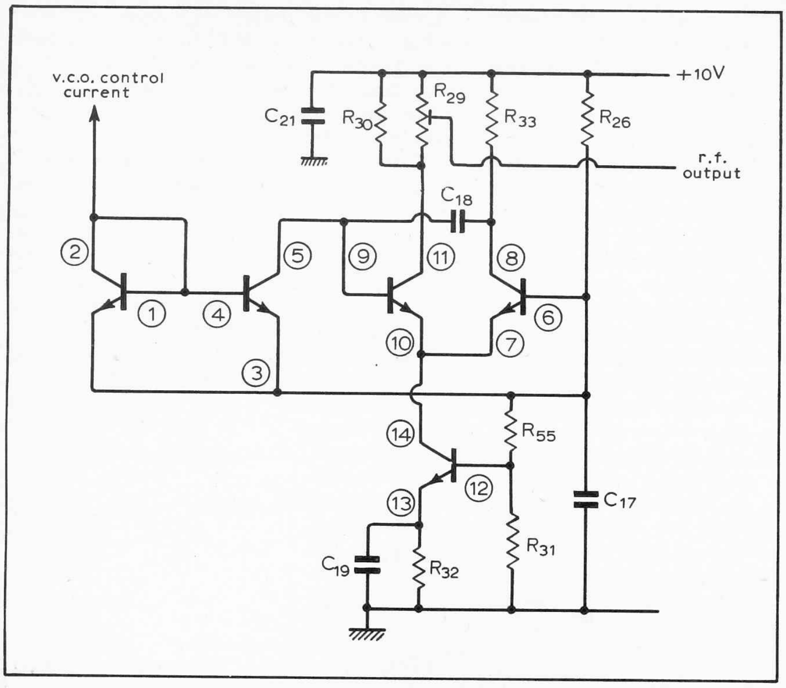
The output of the first ceramic filter is taken to an integrated circuit amplifier, IC_1, (Motorola MFC 4010A) which gives a voltage gain of the order of 100–150 at 10.7 MHz into a 3.3kΩ load. A simple emitter follower is used as the output impedance converter stage between this and the second ceramic filter, with a resistor interposed in the base lead to compensate for the negative input impedance which arises for the reasons mentioned above.

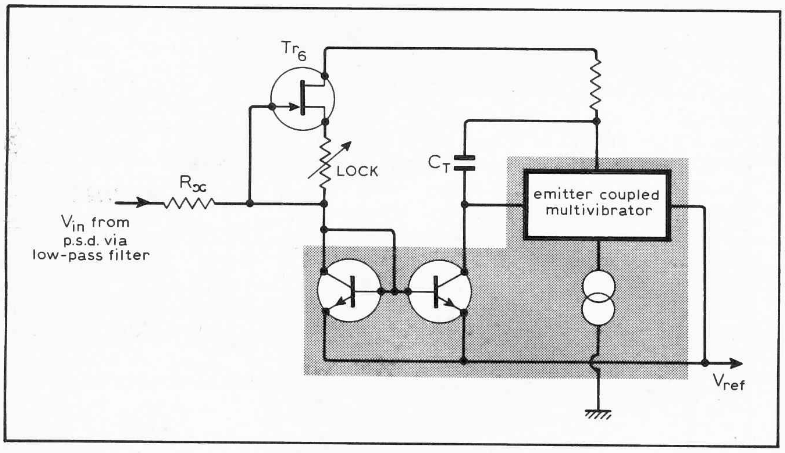
The output from the second ceramic filter is taken to the phase locked loop (IC_2 and IC_3).

Some curtailment of the required stereo pass band is caused by the use of a double ceramic filter arrangement, which has the effect of somewhat reducing the stereo separation at higher audio frequencies in a normal f.m. demodulator system. Because of the capture characteristics of the p.l.l. this phenomenon is less important except

Fig. 3. IC_2 and IC_3 connected to form a complete p.l.l. demodulator.







in the case of a weak signal, and the extra selectivity of the dual filter arrangement is very useful at times—for example, in listening to continental broadcasts within the five or six station group on each BBC programme channel. Although on normal f.m. receivers a "programme" can usually be received over a broadish band, with adequate selectivity this "programme" band can be resolved into the individual adjacent stations, often with gaps between.

If the local signal strength is good, and a lower sensitivity receiver is adequate, the p.l.l. demodulator can be fed directly from the output of the first ceramic filter with IC_1, Tr_3 and the second ceramic filter omitted.

The demodulator. This consists of two integrated circuits, a Motorola MC 1351 (IC_2) and an RCA CA 3046 (IC_3). The first of these performs the functions of i.f. limiting amplifier, phase-sensitive detector, and a.f. preamplifier. The second is a five-transistor monolithic array, connected to operate as a voltage- (or more strictly current-) controlled oscillator.

The block diagram arrangement of the connexions is shown in Fig. 3. Since the operation of the v.c.o. has already been described[2], this is not shown in detail, and the reader is referred to the earlier article.

The d.c. or modulation output from the p.s.d. is taken from pin 2, with a p.n.p. Darlington-transistor emitter follower used as a d.c. level shifter, between the p.s.d. and the v.c.o. input. A simple *CR* network is used as the p.l.l. low-pass filter in this path, and has a time constant chosen to pass the required stereo signal bandwidth. The use of a more sophisticated filter at this point would undoubtedly make some improvement in the capture characteristics and signal-to-noise ratio of the loop, and this is a field in which the constructor can fruitfully experiment. The a.f. output from the p.l.l. is also taken from this point, and is reintroduced into the amplifier section of the MC 1351 which is

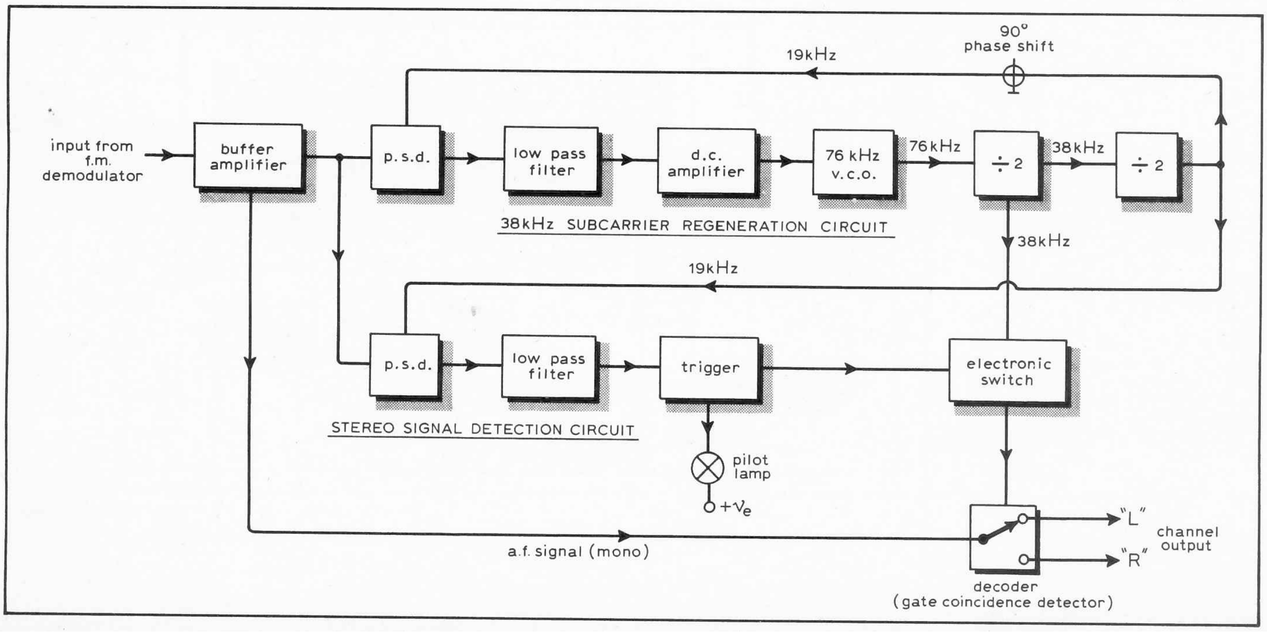


Fig. 4. The CA 3046 integrated transistor array arranged as a v.c.o. The "current mirror" enables a control current into pin 2 to produce an equal current into pins 5 and 9.

Fig. 5. Interface between the "current mirror" and p.s.d., with the components inside the CA3046 indicated. R_x converts the voltage output from the p.s.d. into a current to augment or decrease the current from Tr_7.

Fig. 6. The MC1310 stereo decoder in diagrammatic form.

connected as a bandwidth limited ×5 amplifier, giving a peak a.f. output of about 250mV r.m.s. on a normally-modulated carrier. The harmonic distortion up to this point is better than 0.1% for a ±50kHz modulated carrier at the input of the 10.7-MHz i.f. strip, and better than 0.15% t.h.d. for the full ±75kHz maximum deviation. This compares with the 5–10% t.h.d. of the typical inexpensive f.m. tuner strip without limiter, and the 0.6–1.2% t.h.d. found in carefully aligned and costly f.m. tuner systems using conventional ratio- or quadrature coil gate-coincidence-detector systems. Since, in general, the modulation width is much less than ±75kHz on normal programme material, these figures are obviously "worst case" ones.

Operation of v.c.o. As mentioned earlier, although the arrangement used with the CA 3046 transistor array is referred to as a "voltage-controlled oscillator", the operation of the "current mirror" timing circuit used in this (Fig. 4) is really that of a current input device, and the interface circuit shown in Fig. 5 is used to convert the voltage output of the p.s.d. into an appropriate input for the "current controlled" oscillator. In this, an f.e.t. (Tr_7), is used as an adjustable constant-current source, and the effect of the varying voltage applied to R_x is such as either to add to or to subtract from the current flowing from the constant current source into the current mirror. In setting up, the only adjustment necessary in the i.f. strip or demodulator is to adjust the variable resistor in the source lead of the f.e.t. (Tr_7) to select the appropriate lock frequency for the p.l.l. A technique for doing this is described later.

Stereo decoding. Several techniques exist for this function, but of these the most elegant is a further phase-locked loop such as the excellent system described in *Wireless World* by Portus and Haywood.[3] A virtually identical system to this is now available in integrated circuit form from National Semiconductors (LM1310) and Motorola (MC 1310). This latter device is readily available and inexpensive, and performs the decoder function effectively and unambiguously, and with very little worsening of the overall harmonic distortion figure. This device is used on the prototype, and the circuit arrangement is shown in Fig. 6.

The basic technique of operation of this is similar in form to the phase-locked loop shown in Fig. 1, but with the v.c.o. now running at four times the frequency of the input signal. Since the input signal is the 19 kHz pilot tone, the controlled oscillator is made to operate at 76 kHz. This is fed into two successive divide-by-two stages to give a 19kHz output which is fed into the reference input of the p.s.d. A 90° phase shift is inserted in the 19kHz reference line so that when the two signals (the pilot tone and the ÷4 76kHz signal) are in phase synchronism there is zero output from the p.s.d. This ensures that the phase relationship between the pilot tone and the reconstructed 38kHz decoder switching signal is correct, which is important. Exact unity of the mark-to-space ratio of the 38kHz square wave is ensured by the division down from the 76kHz original oscillator signal.

A further p.s.d. within the circuit is used to sense whether there is phase coherence between the input signal and the 19kHz derived waveform, and is used to switch both a gate-coincidence type decoder circuit and a pilot light into operation. Obviously, in the absence of a pilot tone, indicating a stereo broadcast, this phase coincidence cannot exist, and the decoder circuit remains inactive. A connexion diagram for this type of decoder is shown in Fig. 7.

● *Continued on pages 111/112*

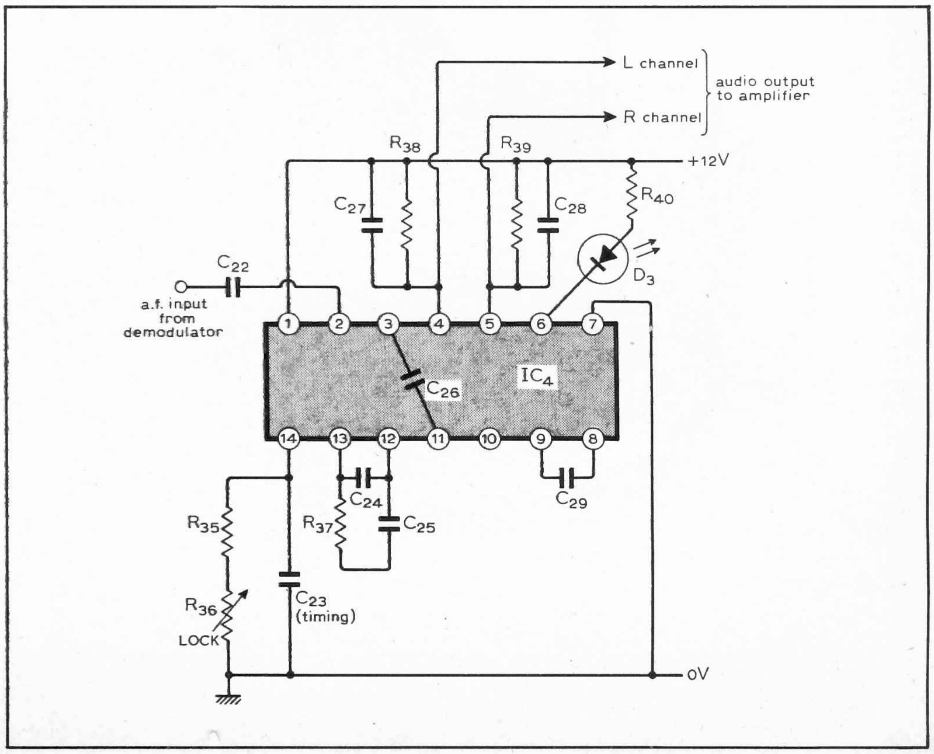


Fig. 7. Connexions for the MC1310P, viewed from below. A 50µs de-emphasis time-constant is used, set by the *CR* networks on pins 4 and 5.

PARTS LIST

I.f. AMP

R_1 39kΩ	C_1 0.1μF	D_1 10V zener BZY88 10V
R_2 18kΩ	C_2 0.1μF	
R_3 39kΩ	C_3 0.1μF	
R_4 220Ω	C_4 0.1μF	IC_1 MFC 4010
R_5 120Ω	C_5 0.1μF	
R_6 330Ω	C_6 10μF 25V tant	F_1 Vernitron FM4
R_7 100Ω		F_2 Vernitron FM4
R_8 330Ω		
R_9 470Ω		
R_{10} 3.3kΩ		
R_{11} 4.7kΩ		
R_{12} 1.8kΩ		
R_{13} 390Ω		
R_{14} 120Ω		
R_{15} 47Ω		

P.l.l.

R_{16} 390Ω	C_7 1nF	Tr_4 MPSA65
R_{17} 3.3kΩ	C_8 0.1μF	Tr_5 2N5457/BC264L
R_{18} 100Ω	C_9 0.1μF	
R_{19} 100kΩ	C_{10} 0.1μF	D_2 10V zener BZY 88 10V
R_{20} 1.5kΩ	C_{11} 250μF 20V tant	
R_{21} 33kΩ	C_{12} 15pF	
R_{22} 12kΩ	C_{13} 0.47μF	IC_2 MC1315
R_{23} 680Ω	C_{14} 1nF	IC_3 CA3046
R_{24} 2.2kΩ	$C15$ 1μF tant	
R_{25} 68kΩ	C_{16} 100pF	
R_{26} 3.3kΩ	C_{17} 0.1μF	
R_{27} 20kΩ cermet preset	C_{18} 10pF	
	C_{19} 0.1μF	
R_{28} 470Ω	C_{20} 33pF mica	
R_{29} 500Ω cermet preset	C_{21} 0.1μF	
R_{30} 1kΩ		
R_{31} 1kΩ		
R_{32} 220Ω		
R_{33} 470Ω		
R_{34} 100Ω		
R_{55} 1kΩ		

P.s.u.

R_{74} 4.7kΩ	C_{50} 470μF 40V	Tr_9 2N3055
R_{75} 33kΩ	C_{51} 250μF 16V	Tr_{10} BC182
R_{76} 33kΩ	C_{52} 0.02μF	
R_{77} 4.7Ω	C_{53} 470μF 25V	D_{11} WO4N7731
R_{78} 470Ω	C_{54} 0.02μF	IC_6 741
		D_{12} 15V zener
		T_1 20V twin RS (MinTr 20V)

Stereo decoder

R_{35} 15kΩ	C_{22} 2μF	D_3 l.e.d.
R_{36} 10kΩ preset	C_{23} 470pF	
R_{37} 1kΩ	C_{24} 0.22μF	IC_4 MC1310P
R_{38} 3.3kΩ	C_{25} 0.47μF	
R_{39} 3.3kΩ	C_{26} 0.047μF	
R_{40} 220Ω	C_{27} 0.015μF	
	C_{28} 0.015μF	
	C_{29} 0.22μF	

Gen arrangement

R_{45} 220Ω	C_{34} 250μF 20V
	D_5 10V zener BZY88 10V

Double p.l.l.

R_{56} 330Ω	C_{37} 10pF
R_{57} 10Ω	C_{38} 0.47μF
R_{58} 1kΩ	C_{39} 47pF
R_{59} 22kΩ	
R_{60} 2.2kΩ	

Tuner

R_{62} 4.7kΩ	C_{39} 10nF disc ceramic	Tr_6 MPSA14
R_{63} 10kΩ 10-turn linear	C_{40} 0.1μF	
	C_{41} 100μF tant	

Muter

R_{64} 47Ω	C_{42} 1nF	Tr_7 BC184
R_{65} 1kΩ	C_{43} 100μF tant	Tr_8 BC264LA
R_{66} 3.3kΩ	C_{44} 0.1μF	
R_{67} 39kΩ	C_{45} 1μF	D_8 0A95
R_{68} 8.2kΩ	C_{46} 10μF	D_9 0A95
R_{69} 100kΩ	C_{47} 0.2μF	D_{10} 3V zener BZY88 3V
R_{70} 100kΩ	C_{48} 0.1μF	
R_{71} 100Ω	C_{49} 2μF	
R_{72} 100kΩ		
R_{73} 10kΩ		

All resistors are ¼W carbon film types, unless described otherwise. Electrolytic capacitors are of the tantalum bead type, while miniature ceramics are used for the small decoupling capacitors.
The author has arranged a supply of p.c.bs and kits of parts with Teleradio.

A phase-locked loop f.m. tuner

● *Continued from page 73*

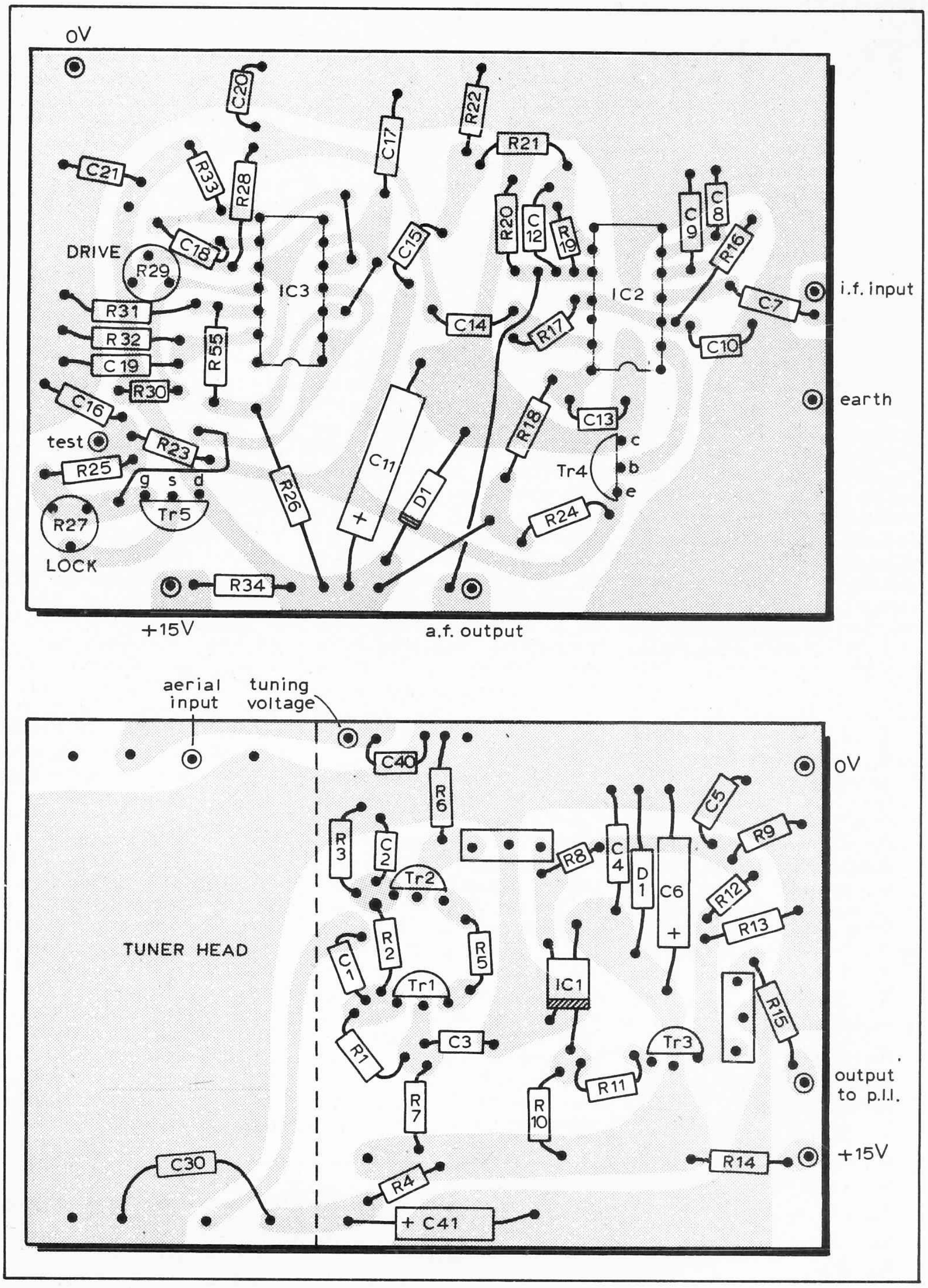


Fig. 8. P.c. board layouts for the p.l.l. and front end/i.f. amplifier. The 10nF decoupling capacitor C_{30} is mounted on the copper side when the Mullard LP1186 head is used.

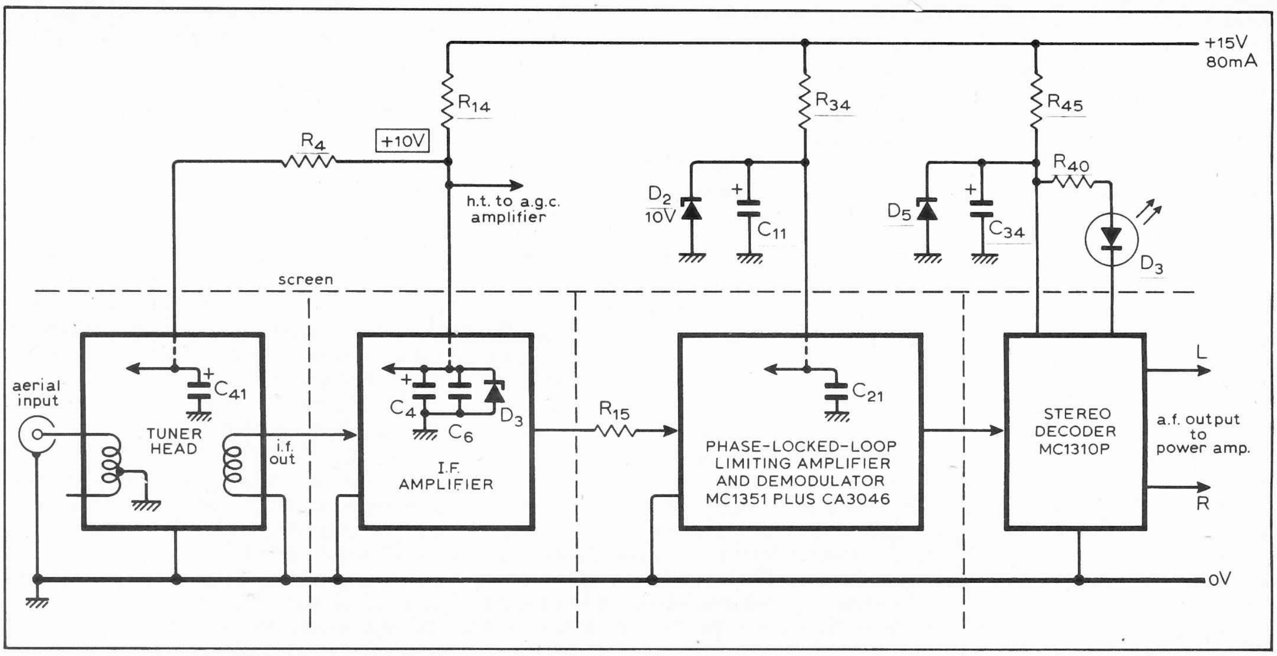
Construction and use

As mentioned earlier, a commercially-available tuner "head" was used with the prototype, and in fact several different head units have been used by constructors of subsequent models of this receiver, with good results. It is thought that the Mullard LP 1186 voltage-controlled tuner, which is currently available and has a good performance, would be a satisfactory choice for those not wishing to build a head unit for themselves from one or other of the published circuits. Whichever head unit is employed it is very desirable that this should be fully screened, with output leads for the 10.7MHz i.f., and input leads for the aerial and supply voltages being the only external points.

The p.l.l.-type demodulator suffers from the snag that there is a voltage-controlled oscillator delivering a volt or two of square wave output at a frequency which is synchronous with the i.f. input, and rich in harmonics which will lie within the f.m. r.f. band. It is essential therefore, in order to avoid "birdies" due to r.f. interference, or instability due to pick up at the input to the i.f. strip (a 5μV level), that the v.c.o. is very well screened. This was done in both models which I built for myself by putting the whole i.f. strip, demodulator and decoder in a die-cast aluminium box (ITT type 0075F) with internal planar partitions to isolate the three separate sections shown in Figs. 2, 3 and 6.

The head and the i.f. box (or boxes) are then mounted on a common aluminium base, in such a manner that the leads from the head to the box are short, and go directly to the relevant points within the box.

The layout of the i.f. amplifier and phase locked loop sections of the circuit is fairly critical if instability is to be avoided, and a diagram is given (Fig. 8) of a printed circuit



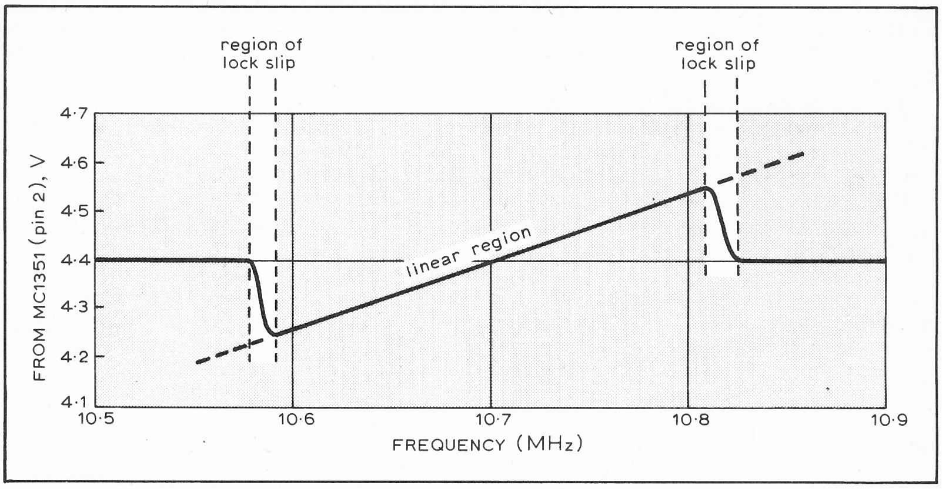


Fig. 9. Power supply feed and layout of units in box.

Fig. 10. The measured demodulator characteristic. Linearity is better than 0.8% per MHz.

connexion and component layout for these two sections which is satisfactory for this purpose, and which is equal in performance to the pin-board layouts used with the first prototypes.

The r.f. i.f. board is in a form suitable for use with the Mullard LP 1186 Varicap tuner head unit, although other units may be used equally well, as available. If the Mullard unit is used, no a.g.c. is employed, and the tuning voltage to the head "TV" input is fed from a Darlington emitter follower to compensate for the thermal characteristics of the Varicap diodes (approx. 500 p.p.m./°C). If an alternative head unit is used, that part of the p.c.b. to the left of the dotted line should be ignored.

The "test" point on the p.l.l. board is used to check the d.c. output from the p.l.l. if a signal generator is available to verify the loop linearity characteristics. In this case, the voltmeter or oscilloscope should be connected via a 10kΩ resistor to avoid modifying the loop characteristics. The loop filter characteristics can be modified, if required, by the connexion of an *RC* network from this point to earth (0.005μF in series with 47 ohms) if loop bandwidth limitation is required.

The p.c.b.s are earthed to the chassis by the three screw (4BA) fixing holes on each board. Normal precautions in building high gain r.f. circuits, in keeping signal leads short, keeping inputs as far away from outputs as practicable, and keeping earth and decoupling leads short, of heavy gauge, and to a secure earth point such as the chassis.

A separate, fairly well smoothed h.t. supply was used for the complete f.m. receiver, but mainly for convenience in that there was no spare h.t. capacity available from the audio amplifier equipment with which this was used. A normal preamp. 15–20 volt line would serve if available at the 60–70mA level.

A suggested layout of the h.t. supplies to, and the screening between the individual circuit modules is shown in Fig. 9. Although somewhat lavish use has been made of zener diode supply stabilisation this only adds about 60p to the total component cost, and contributes to the long-term stability of performance. The measured performance of the demodulator system is shown in Fig. 10.

In use, the performance of the receiver

has been very satisfactory, both in respect of tonal quality and in sensitivity and selectivity. Direct Radio 3 broadcasts from live players are normally remarkably vivid and realistic, and at times the quality of the sound has been significantly better than that from l.p. discs. This is a bit variable, as one might expect, and the quality of some of the recorded broadcasts is often most disappointing by comparison.

On a fairly typical evening, some 25–30 well-defined and separate f.m. broadcast signals can be received in my home, which is not very well sited for f.m. reception, and which is equipped with a single "quad"-type loop aerial, of the general form of that shown in the *Wireless World* diary, page 24, but made from 12in cooking foil taped to form a square of side 3ft 8in outside dimensions on a 4ft square sheet of hardboard. There is a 1in wide gap in the middle of the lower (or upper) strip, across which the connexions to the coaxial feeder are taken. A reflector can be made by the same system if the square of foil on the hardboard is made to have an outside dimension of 3ft 11in and it is mounted 23in behind the receiver loop. The reflector loop is a continuous one. Such an arrangement is better than a four element array of conventional type, although only suitable for loft installation.

Of the signals received with this equipment on a normal day, some four or five will be continentals, at a range of 150 miles or more, and probably two-thirds of the received signals will be of good listening strength and s/n ratio. Since my signal generator has a leakage field of about 4μV, I have not measured the aerial sensitivity, but calculated values, corroborated by the observed performance, suggest that the loop captures at signal levels substantially below 1μV.

A minor source of indignation is that there are several French stations in the 95–98MHz band, which can have programmes of good listening value. Unfortunately, this part of the Band 11 spectrum is also used, for unknown reasons, by the local police forces, so that the programme to which one is listening may be completely obliterated from time to time by relatively powerful local signals. Since the a.m. rejection of the system is good, the a.m. transmissions of the police appear as unmodulated carriers, unless by chance one is tuned to the edge of the transmission band. Nevertheless, the probability of periodic obliteration of the signal reduces the value of the broadcasts which can be received in this part of the waveband.

Setting up

Setting up the demodulator is fairly simple in practice, even without instruments, since some signal will almost certainly be received even when the system is incorrectly adjusted, and all that is necessary is to rotate the "lock" potentiometer, while tuning slowly backwards and forwards through a suitable fairly weak signal, until a position is found at which the signal strength and quality is better than elsewhere. For the purpose of this adjustment, the "drive" pot (between the v.c.o. output and the r.f. input to the p.s.d.) may be set at about halfway.

When the lock is correctly set, the signal strength should remain absolutely constant as one tunes through the signal, and the "plop" on coming into, and leaving a station should be of approximately equal magnitude. Having done this, the tuner should be detuned to a position between signals, or the aerial input removed, and the drive pot. adjusted for the lowest background noise level. If minor adjustments are made both to this and to the lock, an optimum position for both should be found at which the on-signal and off-signal s/n and noise levels are satisfactory. A method of obtaining almost complete inter-station background noise suppression is described in Appendix 1. After having found the approximately correct lock potentiometer position, the use of a fairly short aerial wire—3in to 6in long—will probably assist in fine adjustments.

The use of a miniature cermet potentiometer for the lock control is recommended, for stability of setting with time (once adjusted, it should not require further attention), and a lower-value pot. can, if desired, be connected in series with this to facilitate fine adjustments. The 470ohm resistor/30pF capacitor combination in series with the drive circuit serves to provide a saw-tooth drive waveform to the p.s.d., which assists its operation. The 30pF capacitor should be a non-inductive type (e.g. silvered mica) as should the other decoupling capacitors, for which miniature ceramic types are preferred, and the 30pF should be taken to a chassis earth point, for best results.

Because of the capture characteristics of the loop, a.f.c. should not normally be necessary, unless thermal drift of operating frequency of the tuner head takes it outside the 150kHz pass band of the i.f. strip. This drift may occur in "Varicap" tuner heads, due to the temperature coefficient of the capacitance of the diodes (about 400 p.p.m./°C), but this may be compensated for by driving the Varicap diode tuning circuit through a pair of forward-biased silicon p–n junctions, such as a Darlington-connected emitter follower. With a solid-state tuner head using ganged capacitors, the long-term stability is likely to be entirely adequate without further measures. If an a.f.c. circuit is required, a suitable arrangement can be made by putting a small resistor in the collector circuit of Tr_6, and using this to provide the input to a 741 type operational amplifier. For a tuning meter, a direct voltage can be taken, through a suitable isolating resistor, from the emitter of Tr_6 to an operational amplifier powered from the +10 volt rail. Alternatively, a pair of l.e.ds may be used at the output of the op. amp. instead of a meter.

One snag which should be mentioned, and which appears to be an inherent feature of a p.l.l. demodulator, is that if multi-path reception occurs, say for example because of strong reflections of the signal from local hills or a gas holder, so that the receiver is presented with several signals nearly equal in magnitude but differing in time delay, the loop may "jump" from one to another rapidly as the frequency modulation modifies their relative amplitudes, and this produces severe discontinuity-type distortion, with a characteristically "cracked" sound. Some improvement can be made to this by a more complex loop filter, but the main solution is to improve the directivity of the aerial to make one path the preferred one. In this case the loop will lock selectively onto this, and the distortion will disappear entirely. In this respect the p.l.l. system is better than the normal discriminator which also suffers from multipath distortion where circumstances cause this, but because the discriminator normally acts as an averaging device, while it is not as bad for equal strength signals, improving the strength of one of these cannot wholly remove this defect.

Appendix 1.

Inter-station noise suppression

A phase-locked loop operates by causing a frequency-controlled oscillator to follow the phase and frequency deviations of an input (control) signal. If the preceding amplifier stages have a high gain and are amplitude-limited, any noise signal present will be frequency modulated, and will have a peak frequency deviation equal to the input bandwidth. This will be seen by the loop as a rate-of-change characteristic. If the loop is able to lock onto, and follow this noise signal, the audio output noise will be equivalent to a fully-modulated signal of that bandwidth.

However, if the noise bandwidth (=the input bandwidth) is greater than the p.l.l. bandwidth, loop lock will be lost on a proportion of the input noise excursions, and the audio noise output will be reduced. In the case of the system described above, or any other design using two ceramic filters, the input bandwidth is only just adequate to pass the desired stereo signal, and no further limitation of p.l.l. tracking ability, by the use of a loop low-pass filter, is desirable. In this case therefore, the loop filter is given a time constant which only serves to remove the unwanted r.f. components. (The main reason for using a double ceramic filter system, apart from the additional selectivity which is sometimes useful, is to preclude the possibility of two adjacent frequency signals reaching the limiter stages, where cross-modulation would occur.)

This is not the only possibility of capture limitation available, since the v.c.o. excursion is dependent on the range of the input voltage fed to it, which depends on the p.s.d. output, which in turn depends on the magnitude of the two signals fed to the p.s.d. Since the signal input is limited, this is of constant magnitude. If one now reduces the output of the v.c.o. to the p.s.d. (the drive voltage), eventually the p.s.d. output voltage excursion becomes inadequate to swing the v.c.o. over the whole range necessary to follow the input signal and the noise output is reduced substantially.

Some interesting points arise from these facts.

1. If a fairly wide-bandwidth input circuit is used, and the loop bandwidth is limited by the loop low-pass filter to a value which is less than this, a very good inter-station background noise level is obtained. Experiments have given 30dB quieting of inter-station noise with a 200kHz loop bandwidth and a 500kHz input bandwidth (using the p.l.l. driven directly from a tuner head).

2. Uniquely among f.m. demodulator systems, a p.l.l. does *not* require pre-demodulator limiting to eliminate distortion arising from peakiness of tuned circuits in preceding stages, in that so long as the loop is in lock, the p.s.d. output voltage can *only* be the correct v.c.o. drive voltage for the synchronous frequency required. If the input signal varies in amplitude as the frequency varies, the relative phase of the input signal and the v.c.o. will be automatically and instantaneously adjusted by the loop feedback circuit to give the correct p.s.d. output (audio) voltage for the linear demodulation of the signal.

By the use of the techniques noted above, a p.l.l. f.m. demodulator can be made to give a better off-station background noise suppression than other demodulator systems,

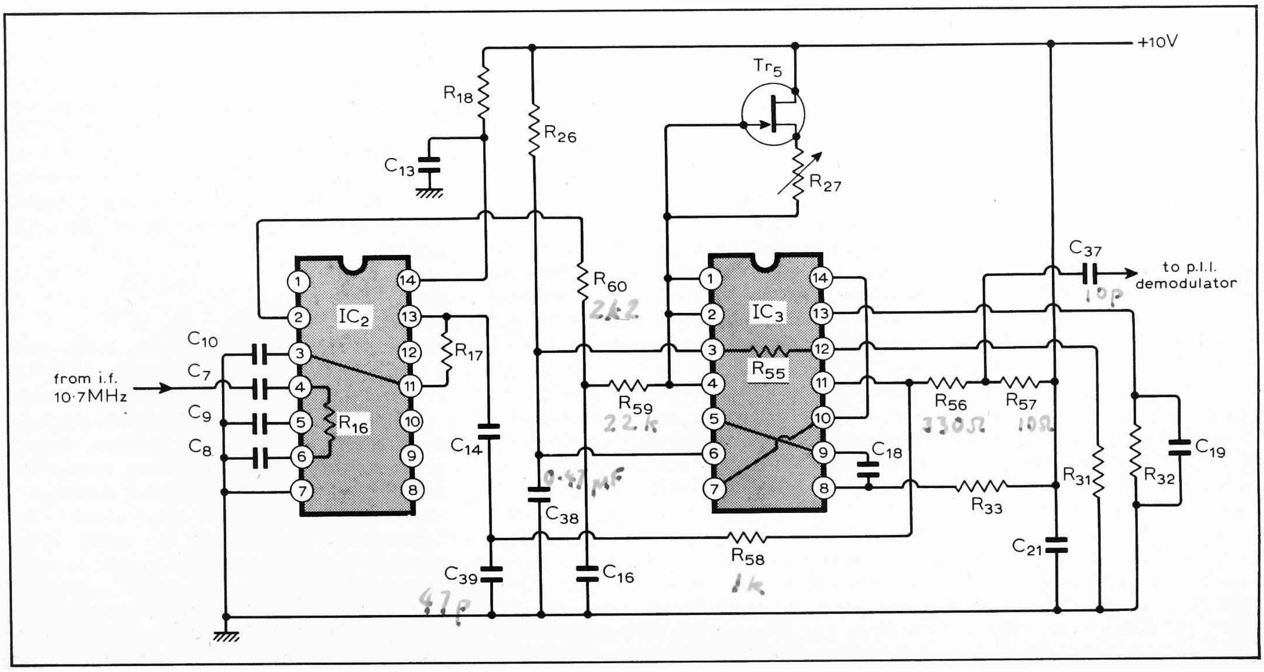


Fig. 11. A simplified version of Fig. 3, showing the use of two p.l.ls in a signal conditioning system.