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Elimination of False-Locking in Long Loop Phase-Locked Receivers

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Abstract—Although long-loop phase-locked techniques are finding increasing application in the fields of mobile radio and satellite communications, their use has several drawbacks. Time delay associated with filtering processes within the loop gives rise to a degradation in acquisition capability, and information components entering the control loop cause a reduction in adjacent channel performance. In this paper, a split-loop technique is described, which eliminates false-locking, substantially improves the acquisition characteristics to that associated with a loop with zero time delay, and "cleans up" the first local oscillator spectrum. Furthermore, the technique is simple to implement.

I. INTRODUCTION

IN recent years, phase-locked techniques have found wide application in receiver design, for example, in satellite [1] and land mobile [2] communication systems. It has often been necessary to incorporate the intermediate frequency (IF) amplifier stages of a superheterodyne receiver within the phase-locked loop, thereby allowing frequency control of the first local oscillator. This configuration is called a long-loop receiver [3] and is shown in the simplified block diagram form of Fig. 1. For such a system, once phase-lock is achieved, $\omega_r = (\omega_i - \omega_0)$ and the received information is correctly positioned within the narrow IF crystal filter. Furthermore, it should be possible to track out frequency changes due to Doppler or oscillator drift. Unfortunately, the excess phase shift introduced into the loop by the IF filter can cause a significant deterioration in the loop's acquisition and tracking characteristics. In particular, a phenonemon known as false-locking [4] may occur whereby synchronization is never achieved and incorrect signal demodulation results.

Although some fundamental work in this area has been undertaken, notably by Develet [5] and Jelonek *et al.* [6], little published work exists in its application to long-loop superheterodyne receivers with the exception of that by Biswas *et al.* [7]. These authors suggest a technique by which false-locking may be eliminated which will be discussed more fully in the next section. Although somewhat complex, the method is nonetheless significant in that it is a positive design response for radio frequency engineers attempting to use long-loop phase-locked receivers. At this time, such work is particularly relevant because of the renewed interest in using 5 kHz single sideband modulation in the land mobile services of North America and the United Kingdom. The three methods

presently under investigation differ essentially in the positioning of the pilot tone (required for automatic frequency control and automatic gain control) within the audio band. They are pilot carrier SSB [8], [9], tone-in-band SSB [10], and tone-above-band SSB [11]. Although each system has advantages and disadvantages, it is now generally accepted that each receiver type requires the use of a long-loop phase-locked receiver if correct demodulation and an economically viable receiver design are to be achieved. Failure to incorporate the first local oscillator within the loop can lead to "sideband cutting" by the IF crystal filter. Since it is also likely that each receiver system will be multichannel, the first local oscillator will use a frequency synthesizer with its own inherent and considerable time delay. This will, of course, degrade further the acquisition and tracking performance of the loop. In addition, any noise or modulation components appearing on the control line of the first local oscillator will spread its output spectrum and, thus, reduce the adjacent channel performance of the receiver, a problem which has been discussed in some detail by McGeehan and Lymer [12].

In this paper, a novel approach to the design of long-loop phase-locked receivers is described whereby both the first and second local oscillators are controlled in a split-loop configuration. Use of this method will be shown, not only to eliminate false-locking, allowing pull-in from much larger frequency offsets, but also to improve the spectral purity of the first local oscillator. The technique has wide application, for example, in satellite and land mobile receivers, and here it is applied to the design of a phase-locked single sideband mobile radio receiver. Finally, the effect of excess time delay on the noise bandwidth of both a conventional and a split-loop receiver is investigated.

II. EFFECT OF TIME DELAY ON PHASE-LOCKED LOOP ACQUISITION

Insight into the false-lock problem may be gained by first considering a commonly used explanation for phase-locked loop pull-in. When out of lock, the output voltage of a phase-locked loop phase detector (neglecting higher frequency terms) consists of a beat note and a dc voltage. The dc voltage causes a gradual reduction in the beat frequency until the lock-in limit is reached and the loop quickly achieves phase-lock. This dc voltage is a product of the input and a VCO sideband of the same frequency. Gardner [13] obtains an accurate expression for the pull-in time of a second-order type-two loop by assuming that the beat frequency passes only through the proportional filter term while the slowly changing dc voltage passes solely through the integrator.
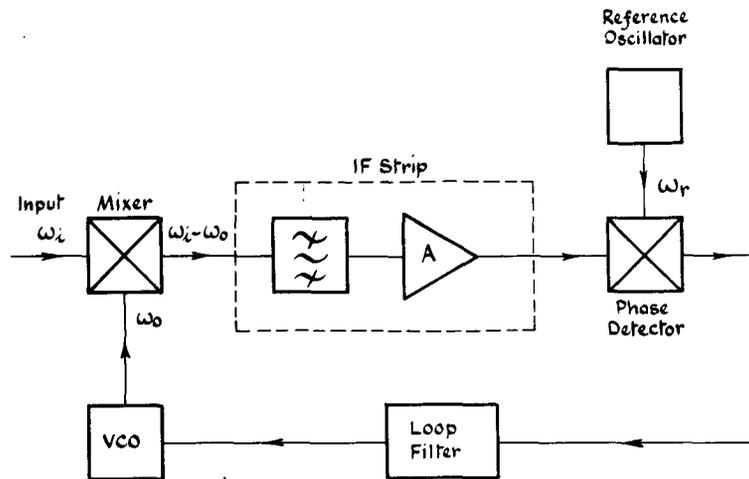
Fig. 1. The long-loop phase-locked receiver.

Now, when considering the effect of additional filtering within the loop, Gardner [4] shows that the increased pull-in times and false-locking are due to excess phase shift in the beat frequency path. Similarly, Develet [5] considers the effect of pure time delay τ on the acquisition performance of a second-order loop and obtains an important result. For a high-gain second-order loop he concludes that the loop will fail to acquire correctly if the initial frequency offset is greater than $1/4\tau$ Hz. Subsequent workers [14], [15] have confirmed this result.

In a method proposed by Biswas et al. [7] for avoiding false-locking, an electronic phase shifter is connected between the IF output and phase detector input in Fig. 1. The phase shifter introduces a phase shift δ proportional to the rectified output of the loop filter. If the excess loop phase shift is equal and opposite to δ, its effect is removed. However, if this is not the case, the loop analysis is greatly complicated by the additional circuitry and no explanation of its behavior has been given. The technique to be described in the next section is easier to implement and does not complicate the loop analysis. Throughout this paper it is assumed that the excess time delay is small compared to the reciprocal of the loop noise bandwidth so that a stable locked condition exists.

III. THE SPLIT-LOOP TECHNIQUE

Several authors have found considerable advantage in "splitting" the filter of a phase-locked loop. Richman [16] originated the method for analysis of loop acquisition. Biswas and Banerjee [17] propose a hybrid-locked loop which includes two VCO's controlled by independent low-pass filters. More recently, Ward [18] has reported improvement in the locking range of a first-order loop by splitting a loop filter into high and low frequency paths. The split-loop technique applied to a phase-locked superheterodyne receiver is shown in schematic form in Fig. 2. It can be seen that the phase detector output controls both the first and second local oscillators through the filters $F_1(s)$ and $F_2(s)$, respectively. Neglecting mixer output sum term components and, for the present, the effect of any excess loop phase shift, it can simply be

shown that

$$\frac{d\phi}{dt} = \Omega + \frac{d\theta i}{dt} - [K_1 F_1(s) + K_2 F_2(s)] K_d \sin \phi \qquad (1)$$

where

$\Omega = \omega_i - \omega_0 - \omega_r,$ the frequency offset

$\phi = (\omega_i - \omega_0 - \omega_r)t + \theta_i - \theta_0 - \theta_r,$

the phase error

and

$$K_d = \frac{V_i V_0 V_r A}{4}.$$

If we now write

$$F(s) = \frac{K_2}{K_1} F_2(s) + F_1(s) \qquad (2)$$

then (1) reduces to that of a phase-locked loop, with loop filter of transfer function $F(s)$, VCO gain K_1, and phase detector constant K_d. Meer [19] states that for a loop filter with equal numbers of poles and zeros it is reasonable to consider the filter as composed of a constant high frequency term and a low-pass term which decays to zero for frequencies outside the loop noise bandwidth. All order filters which are Wiener-optimized for tracking or demodulation in the presence of additive white noise possess this property. Therefore, it is permissible to rewrite (2) as

$$F(s) = \frac{K_2}{K_1} F_2 + F_1(s) \qquad (3)$$

where F_2 is independent of s and $F_1(s)$ is the low-pass term with zero high frequency gain.

The advantage of employing the split-loop technique is apparent when the excess phase shift introduced into the long
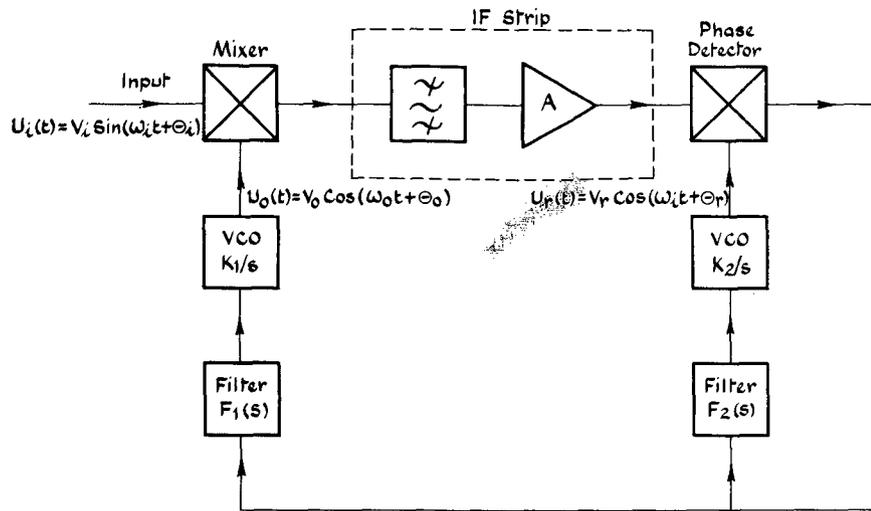
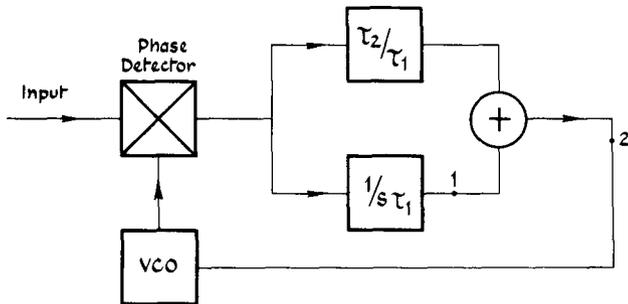Fig. 2.   Configuration of the split-loop phase-locked receiver.

Fig. 3.   Equivalent model of a second-order, type-two phase-locked loop.

loop by the IF stages is taken into account. During the acquisition stage of the long loop, the beat frequency from the phase sensitive detector propagates around the F_2 path, bypassing the IF stages, and, thus, eliminating the possibility of false-locking. To confirm the validity of the method, acquisition time measurements were conducted on an audio second-order type-two phase-locked loop, a block diagram of which is shown in Fig. 3. Here, the loop filter is described by the relationship

$$F(s) = \frac{1 + s\tau_2}{s\tau_1} \qquad (4)$$

where, using (3), $F_2 = \tau_2/\tau_1$ and $F_1(s) = 1/s\tau_1$. By inserting a variable CCD delay line at either points 1 or 2 in Fig. 3, it was possible to simulate either the split or conventional long loop. The loop had a natural frequency of 100 Hz and a damping factor of $1/\sqrt{2}$. The resulting acquisition time-frequency offset measurements for the conventional and split-loops are shown in Figs. 4 and 5, respectively. As expected, Fig. 4 illustrates the dramatic reduction in pull-in range caused by the presence of time delay. However, when the time delay is restricted to the integrator path of the filter, the effect of delay is substantially reduced and false-locking is eliminated. In fact, for large frequency offsets, increasing the time delay up to the stability limit shows negligible effect on acquisition time.
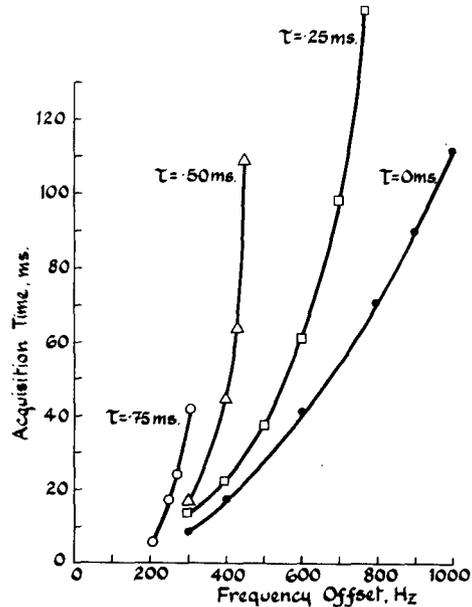

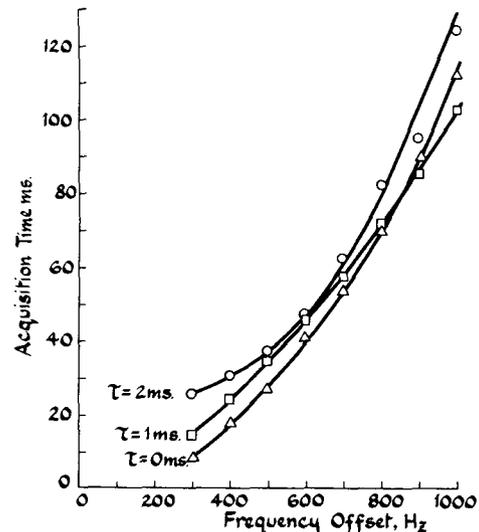Fig. 4.   Acquisition performance of a phase-locked loop with time delay τ.

Fig. 5.   Acquisition performance of a "split" phase-locked loop with time delay τ present in the integrator path.
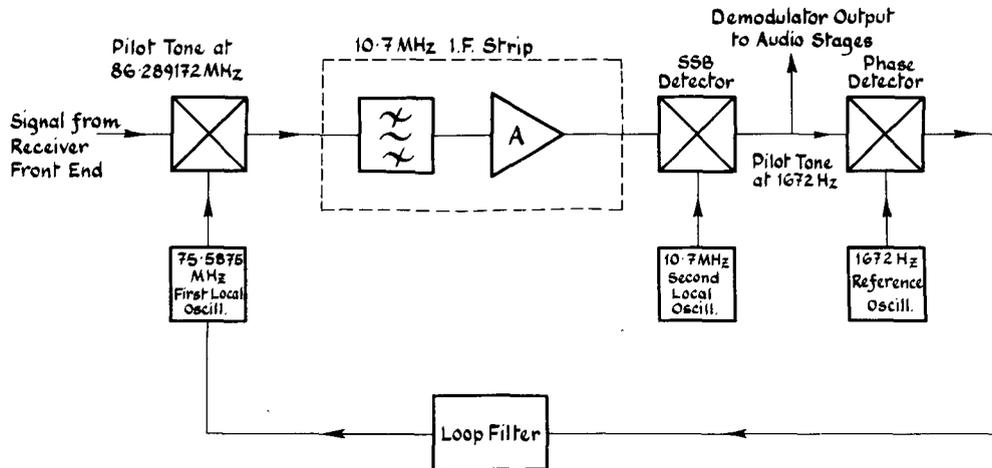
Fig. 6. Conventional long phase-locked loop in the Wolfson tone-in-band VHF single sideband receiver.

IV. APPLICATION OF SPLIT-LOOP TECHNIQUE TO A VHF SSB MOBILE RADIO

In this section, the split-loop technique is applied to the design of the Wolfson tone-in-band VHF SSB land mobile radio receiver developed at the University of Bath. The technique is equally applicable to the pilot carrier and tone-above-band systems.

A. Acquisition Performance

In the Wolfson pilot tone SSB system [10], a tone some 15 dB down on peak envelope power is transmitted in a notch in the midband region of the audio spectrum. The choice of tone frequency is somewhat arbitrary, but frequencies in the range of 1.2–2.5 kHz are acceptable. The tone is used in the receiver for AGC and AFC purposes. In this research work, a tone frequency of 1.672 kHz was used, such that when the received signal was demodulated to audio, the received tone is compared in frequency and phase to an internally generated 1.672 kHz precise reference. A simplified block diagram showing a low-band VHF phase-locked receiver is given in Fig. 6. Additional filtering within the loop, for instance, the IF filter or a tone bandpass filter, has been shown [20] to severely degrade pull-in performance characteristics even when a derived rate rejection acquisition aid [21] is used. The problem is further exacerbated if the first local oscillator frequency is derived from a narrow bandwidth synthesizer.

An 86.2875 MHz receiver, which allowed control of the first or second oscillators or split control with integral control of the first oscillator and proportional control of the second, was constructed. Acquisition measurements were taken for a 100 Hz loop with a damping factor of $1/\sqrt{2}$, thus corresponding to the loop parameters of Section III. The receiver AGC was fixed throughout the experiment. Excess phase shift was introduced into the loop by the SSB IF filter and the first local oscillator channel synthesizer. The IF filter had a measured midband group delay of 0.41 ms at 10.70167 MHz. The phase-locked loop synthesizer was based on the Philips LN123/LN124 integrated circuits with a closed-loop, 3 dB bandwidth of 625 Hz, as recommended in the manufacturer's specifica-
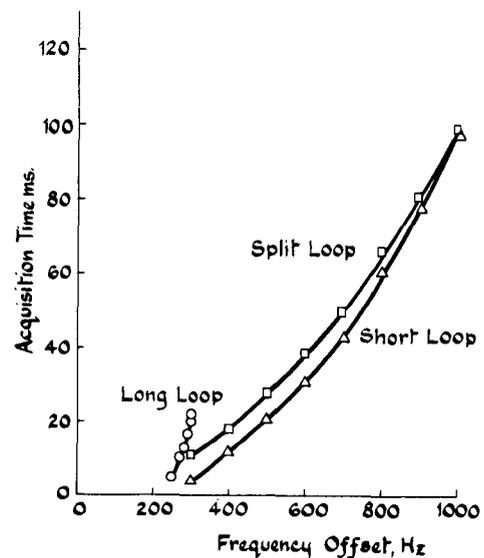

Fig. 7. Comparative acquisition performance of a VHF single sideband receiver for the long-, short-, and split-loop configurations.

tion for 6.25 kHz channel spacing. The experimental results are shown in Fig. 7. For the conventional long-loop receiver, false-locking occurred and acquisition was only possible at frequency offsets up to 300 Hz. For the short (i.e., fixed first local oscillator) and split-loop configurations, acquisition occurred without difficulty. The split-loop results clearly illustrate that the receiver's first local oscillator can acquire large frequency offsets irrespective of the excess loop phase shift.

B. Improvement in Output Spectrum of First Local Oscillator

Modulation components at the SSB detector output, Fig. 6, mix with the reference tone in the phase sensitive detector. The resulting sum and difference phase sensitive detector outputs give rise to sidebands on the first local oscillator. McGeehan and Lymer [12] indicate that this could result in poor adjacent channel protection caused by reciprocal mixing. This form of spurious reception occurs when a side-
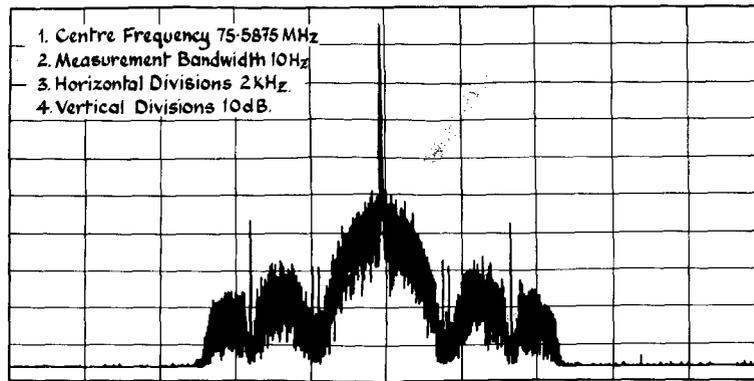
Fig. 8. First local oscillator spectrum of a tone-in-band long-loop SSB receiver.
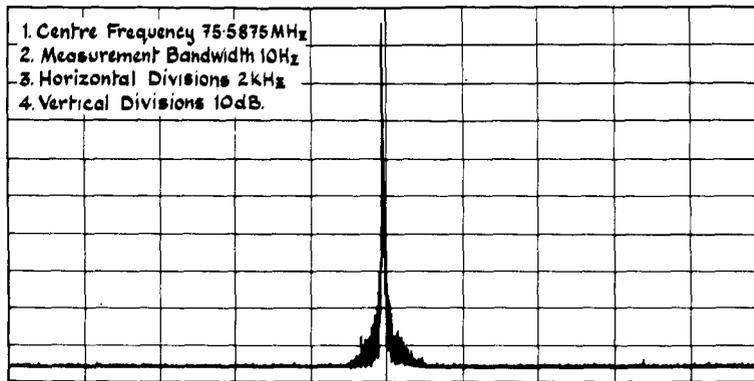

Fig. 9. First local oscillator spectrum of a tone-in-band split-loop SSB receiver.

band on the first local oscillator mixes with an unwanted adjacent channel tone producing a component within the IF crystal filter passband. However, when the split-loop is used, the modulation components mainly degrade the second local oscillator which is protected from the adjacent channel by the IF filter. In the conventional long loop, a tone at frequency ω rad/s, at the phase detector output, frequency modulates the VCO after passing through a low-pass filter described by (4). In the split-loop case the proportional term to the first local oscillator is removed and the filter becomes $F_1(s) = 1/s\tau_1$. It is easily shown that the resultant reduction in the tone level at the first local oscillator input is given by $10 \log_{10} [1 + 4\zeta^2\omega^2/\omega_n^2]$ dB where ω_n is the loop natural frequency and ζ is the loop damping factor. In the current Wolfson SSB system [22], the peak envelope power is limited at 15 dB above the pilot tone in the transmitter and ω_n is set at 2π 10 rad/s. Figs. 8 and 9 depict the output spectra of the first local oscillator of the receiver with conventional and split-long-loop control, respectively, when receiving random noise. The noise was transmitted to simulate speech modulation. The conventional long-loop controlled oscillator spectrum of Fig. 8 shows that the first-order sidebands are evident with terms at ±3.34 kHz offset, twice the pilot tone reference frequency. In Fig. 9, which shows the split-loop controlled first local oscillator, the modulation induced phase noise is only visible up to about 1 kHz offset, 105 dB/Hz below carrier. This performance would not limit the adjacent channel protection ratio that is required for a land mobile radio system.

V. LOOP NOISE BANDWIDTH

The noise bandwidth of a phase-locked loop is given by

$$B_n = \int_0^\infty |H(j2\pi f)|^2 \, df \, \text{Hz} \tag{5}$$

where $H(s)$ is the closed loop transfer function. For a second-order type-two loop with fixed natural frequency ω_n rad/s, the integral has a minimum value at $\omega_n/2$ Hz [23] when ζ is set equal to 0.5. In this paper, the minimization has been computed when the loop contains a pure time delay τ, initially in both filter paths, and second, when the delay is restricted to the integrator path alone. In the first case $H(s)$ is given by

$$H(s) = \frac{\omega_n^2 + 2\zeta\omega_n s}{\omega_n^2 + 2\zeta\omega_n s + e^{s\tau}s^2} \tag{6}$$

and when the delay is restricted to the integrator path

$$H(s) = \frac{e^{-s\tau}\omega_n^2 + 2\zeta\omega_n s}{e^{-s\tau}\omega_n^2 + 2\zeta\omega_n s + s^2}. \tag{7}$$

The integrals were evaluated numerically to a frequency of 300 ω_n rad/s and the resulting curves are given in Fig. 10. Here, the minimum normalized noise bandwidth and the corresponding damping factors required are plotted against delay phase $\omega_n\tau$. For the conventional long loop, the minimum
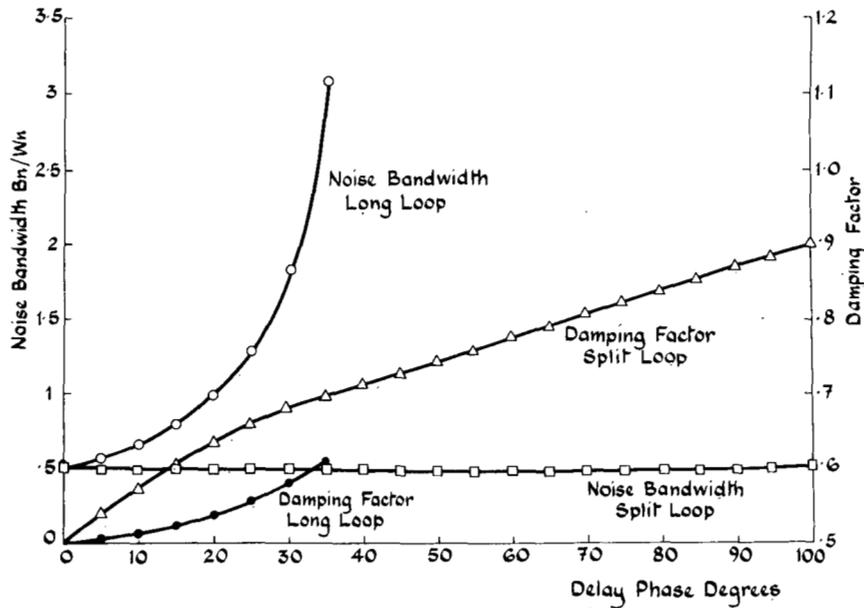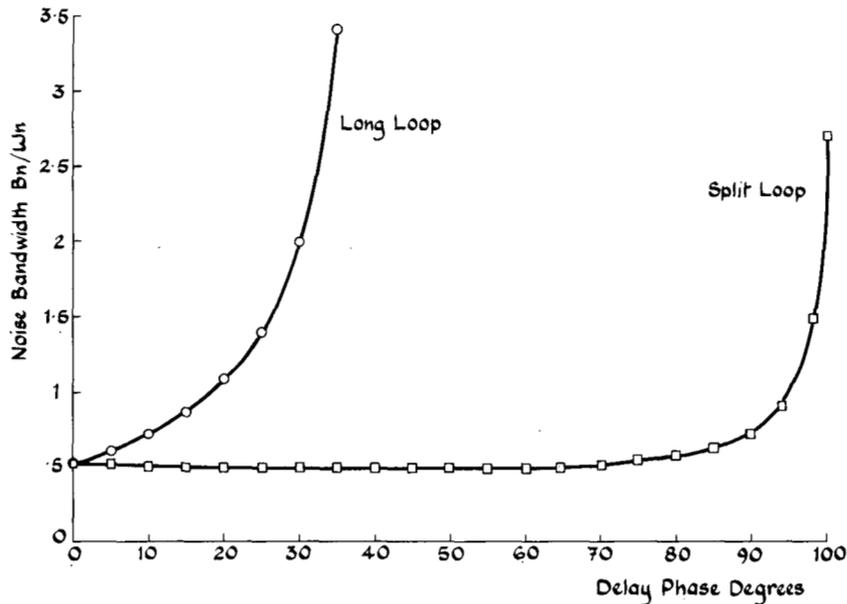
Fig. 10. Effect of time delay on minimum noise bandwidth.

Fig. 11. Effect of time delay on noise bandwidth for a loop damping ratio ζ of $1/\sqrt{2}$.

noise bandwidth steadily increases with the time delay until the loop eventually becomes unstable. The results are similar to those obtained by Frankle and Klapper [24]. However, when the delay is restricted to the integrator path, the minimum noise bandwidth is affected to a negligible extent by the excess delay. Phase-locked receivers are usually designed with a damping factor of $1/\sqrt{2}$, and for this case the variation of noise bandwidth with delay is illustrated in Fig. 11. It can be seen again that the split-loop tolerates large delays before the noise performance is severely degraded.

VI. CONCLUSIONS

In this paper a split-loop technique which overcomes many of the problems associated with conventional long-loop phase-

locked radio receivers has been described. It was shown to eliminate the problem of false-locking and result in a similar acquisition performance to that expected without time delay. The technique is extremely simple to implement in that the only additional circuitry required is a split-loop filter and a low deviation voltage-controlled second local oscillator. Furthermore, the degradation of the first local oscillator spectrum caused by modulation and noise components entering the loop has been shown to be substantially reduced, resulting in an improved adjacent channel performance. When the phase-locked loop contained pure time delay, the noise bandwidth performance was also improved by the use of the split-loop technique.

It is felt that the technique will find immediate application

in the current VHF SSB mobile radios being developed. It should be noted that the time delay generally associated with the pilot carrier and tone-above-band systems is somewhat greater than that for the midband tone system as a consequence of the increased group delay at the edges of IF crystal filter.

ACKNOWLEDGMENT

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In recent years, Dr. McGeehan has served as a member of the U.K. Home Office (Directorate of Radio Technology) Working Group on single sideband land mobile radio and is a member of U.K. Study Group 8A of CCIR. He is a Chartered Engineer and a member of the Institution of Electrical Engineers and the Institute of Electronic and Radio Engineers.

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