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## Chapter 16

# Sampling systems

P. Cochrane

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### 1 INTRODUCTION

The use of wideband sampling in microwave measurements has now become commonplace and has been developing rapidly since the mid 1950's. Looking back to its origins, in many respects, it appears to have been developed principally to overcome the limitations posed by real time oscillography [1-3]. Here Travelling Wave-like Cathode Ray Tubes [4-8] have been developed to display waveforms up to about 7 GHz [5]. These are extremely expensive devices to produce - as evidenced by the fact that currently available commercial units have only in recent years reached 1 GHz bandwidth real time. In contrast, sampling techniques offer the key attractions of being both fast and reasonably priced with currently available commercial units operating up to about 20 GHz.

From these early display applications sampling has been used increasingly to overcome other measurement limitations in voltmeters, power meters, counters, timers and comparison schemes [9-20]. Until recent years the techniques and instruments commonly in use offered only equivalent time (multiple occurrence/Sub-Nyquist) operation. Lately device and circuit developments have made possible instruments capable of real time (single occurrence/Nyquist) sampling [21-23]. However, perhaps the most profound development - for both modes of operation - has been the development of suitable digitizers and subsequent linking to the ubiquitous mini-computer. Next to overcoming fundamental speed limitations, this one step has increased the measurement capability and versatility most dramatically.

In this chapter we review the techniques used in commonly available commercial equipment, and also consider a few examples of instruments developed for research applications. Our purpose in this approach is to try to convey an operational understanding of existing instrumentation and perhaps pre-empt the arrival of new instruments in the laboratory. Throughout we utilise the defined and derived relationships of the previous Chapter

to explain the operation and limitations of specific schemes considered - which have been classified into two broad functional groups; visual display and parametric measurement.

## 2 PRACTICAL SAMPLERS

As the sampler is the key element in all the instruments and techniques described in the text to follow, we briefly consider the realisation of such devices and their practical performance limitations. The space constraint on this text only allows us to consider in detail some commonly used examples. Due reference is thus made to the many varied techniques developed or currently being investigated.

### 2.1 Sample Pulse Generation.

As described in the previous chapter, generating a suitably short sample pulse is fundamental in attaining the required bandwidth. For electrically driven samplers this is sometimes realised using a directional coupler, but more commonly by a short circuit transmission line or cavity as depicted in Fig 1.

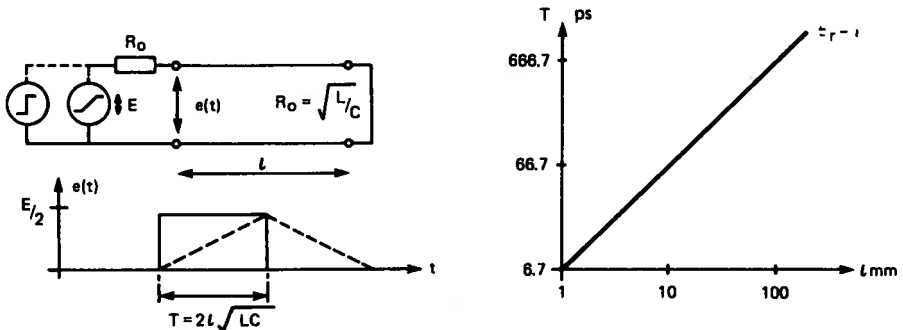


Fig 1 Sample pulse generation using a short circuit line

The step or ramp drive to the transmission line may be generated by a variety of devices; Tunnel Diode ( $T \sim 20$  ps), Avalanche Transistor ( $T \sim 200$  ps), Snap Off or Step Recovery Diode ( $T \sim 100$  ps) and Mercury Wetted Relay ( $T \sim 10$  ps). It is often the case that, in turn these have to be driven or triggered by a high amplitude short duration ( $\tau \sim 10T$ ) transition. In practice a cascade of two or more such circuits may be necessary [24-28].

More recent work with Josephson devices has produced high repetition pulses/samplers with  $T \sim 10$  ps [28-31], and laser pulse driven photoconductive devices have achieved  $T \sim 100$  ps [23]. However, these techniques tend to introduce considerably more complexity - ie cryogenic environment - which so far relegates them to specialised

research applications and we therefore neglect them in the remaining discussion. To avoid unwanted transients due to drive circuit operation and/or mismatches between the short circuit transmission line and an "on device", it has often proved necessary to shape or taper the line/cavity [32-35] as per the example shown in Fig 2. However, a number of commercial and experimental instruments now employ a degree of integration, coupled with thin film construction for this function, which overcomes many of the limitations due to transients generated by stray reactive elements and impedance mismatches [36-38]. A typical sample pulse generator circuit used in a commercial CRO is given in Fig 3. This utilises an avalanche breakdown transistor energised by an NPN transistor strobe device operating with a 30  $\mu$ s period. The avalanche transistor delivers a 40 volt, 5 ns risetime, balanced drive step wave to the snap-off diode, which in turn operates as a current switch delivering a step of about 20 mA (< 40 ps risetime) to the short circuit stub lines.

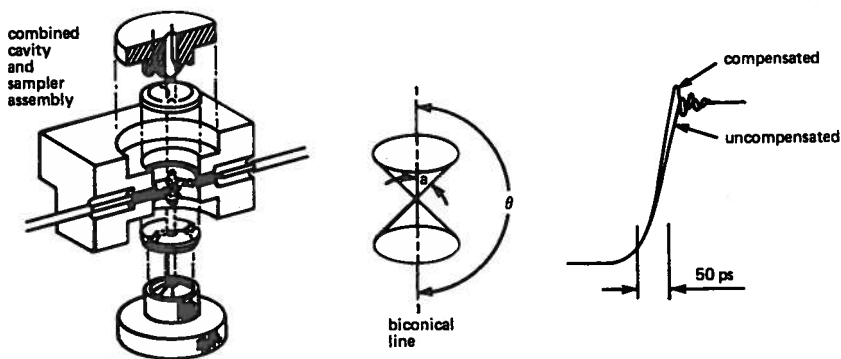


Fig 2 Tapered cavity sampling head

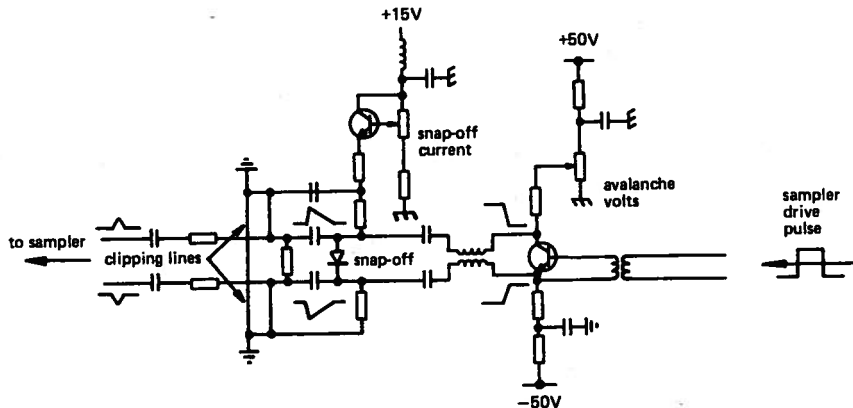


Fig 3 A commercial sample pulse generator

In commercial instrumentation such circuits are generally operated at kHz (Sub-Sampling) rates. However, it is possible to increase the operating rate up to the low MHz region - usually  $< 30$  MHz - before the circuit reaches the power dissipation limit of the avalanche device. Making samplers for real time microwave rates (Nyquist and Super Sampling) can be extremely difficult - and the subsequent signal processing even more so! However, sampling pulse windows of  $< 200$  ps have been achieved at GHz rates using conventional ECL logic drives. Josephson [31] and Optical [22] devices offer the prospect of doing much better in the future.

## 2.2 Sampling Gate.

This part of the hardware may take many forms; from a single unbalanced diode [39], double balanced ring of four [36], to a series of six floating diodes [37] depending on the specific application. The most commonly used devices include the Tunnel, Schottky and Hot-Carrier diodes giving a sampling bandwidth up to about 40 GHz. Recent work with Josephson devices has given a performance extension to about 70 GHz [28].

Generally, the balanced sampler is preferred as it avoids the "kick out" effect and may be realised in a floating earth, dc coupled, configuration as per the examples shown in Fig 4. The term "kick out" is an American expression coined to describe the leakage of the sampling pulse from the sampler. Typically this phenomenon can be suppressed by  $> 35$  dB, by a balanced circuit, which is necessary to prevent interference to, and reflections from, the circuit under test.

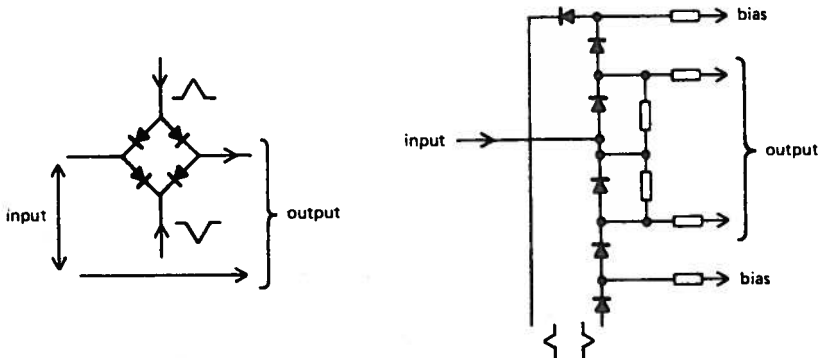


Fig 4 Typical commercial sampling gate configurations

### 2.3 Sampler Circuit Function.

The two diode circuit shown in Fig 5 below is indicative of the types commonly found in commercially available equipment, and serves as a model for further discussion. In this circuit the signal is sampled by balanced strobe pulses applied through the capacitive couplers. Because the input line is floating (ie can be set at an arbitrary dc level) and the signal may be amplitude asymmetric, the diodes can be expected to assume an unequal charge storage state. An output is thus produced that is related to both the amplitude and polarity of the input signal.

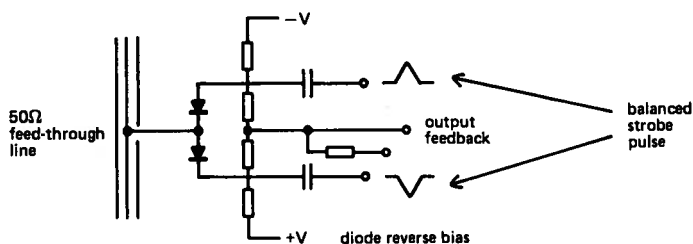


Fig 5 Two-diode sampling gate

A feedback path is provided to reset the reverse bias applied to the diodes after each sampling action so that subsequent samples only detect voltage changes in the input signal. This arrangement increases the dynamic range of the sampler and maintains a near optimum bias.

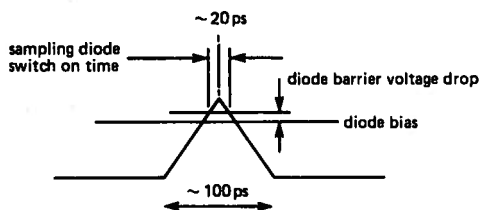


Fig 6 Sampling diode bias

Since the sampler output is proportional to input signal differences, an integrator is required to create an output proportional to the input. In its simplest form the sampler thus appears as shown in Fig 7(a). Taking account of the real-life components a near true equivalent circuit is a good deal more complex as Fig 7(b) indicates.

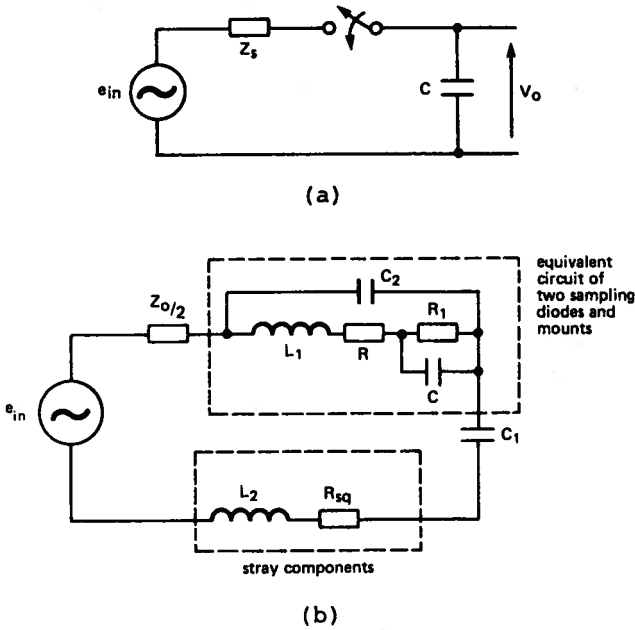


Fig 7 (a) Simple equivalent sampler circuit  
 (b) A real component equivalent circuit

This is an unbalanced equivalent circuit of the two diode balanced array. As demonstrated by Grove [32], this model may be subsequently reduced by assuming  $C_1 \gg C_2$  and that  $C_2$  is anyway masked by embedding the diodes in the dielectric of the transmission line. The equivalent sampling circuit is thus reduced to:-

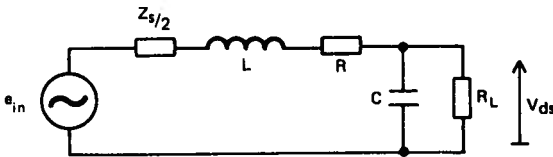


Fig 8 Simplified equivalent circuit for a diode sampling gate

Grove derived a standard form complex frequency domain description for a step input signal:-

$$V_{ds} = \frac{e_{in} \left[ \frac{1}{LC} \right]}{s^2 + s \left[ \frac{R + Z_o/2}{L} \right] + \frac{1}{LC}} = \frac{e_{in} \omega_n^2}{s^2 + 2\delta\omega_n s + \omega_n^2} \dots\dots (1)$$

Using this relationship it is possible to optimise the sampler to give maximum flatness - minimum overshoot for whatever application. As a matter of interest Grove [40] selected the following design values for an optimised 15 GHz design:-

$$\begin{aligned} \delta &= \frac{1}{\sqrt{2}} & L &= 250 \text{ pH} \\ & & C &= 0.2 \text{ pF} \\ Z_o &= 50 \Omega & R &= 10 \Omega \end{aligned}$$

these give an indication of the difficulties of mechanical construction experienced prior to the introduction of integration and thin film technology.

#### 2.4 Sampler Time Domain Analysis.

Whilst the analysis by Grove [32,40] et al [35,41] provides both an adequate design description and switching model, an alternative approach by Nahman [42] provides (in the author's view) a somewhat better picture of the overall operation. Because Nahman's description has only appeared in lecture notes, we briefly reproduce his analysis as follows:-

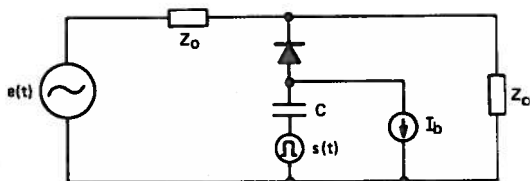


Fig 9 Nahman's single ended model of a balanced sampling gate

The scheme we wish to analyse consists of a uniform transmission line terminated in its characteristic impedance with a sampling gate connected at some point across the line as per Section 2.3. This may be reduced to the equivalent (Thevenin's) signal source and sampling pulse generator circuit shown in Fig 10.

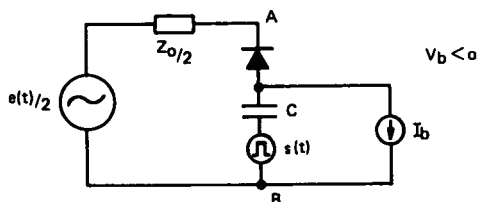


Fig 10 Thevenin equivalent sampler circuit

Here the sampling process requires that  $e(t)$ ,  $s(t)$  and observation of the voltage developed across the capacitor  $C$  be synchronised. The current source  $I_b$  develops a negative potential to keep the diode cut-off, and as a result  $C$  is charged to that bias level  $V_b$  (which is set by the reverse resistance of the diode). For reasons previously discussed, the sampling pulse  $s(t)$  is very narrow and in this application exceeds the magnitude of  $V_b$  with an excess magnitude greater than the peak to peak signal  $e(t)$ . Consequently, the sampling diode is only turned on by the presence of the sampling pulse. When  $s(t)$  is present the diode is rapidly switched "on-off" and behaves as a time dependent resistor  $r(t)$  over the time interval  $t_1 \leq t \leq t_2$  (for a single event).

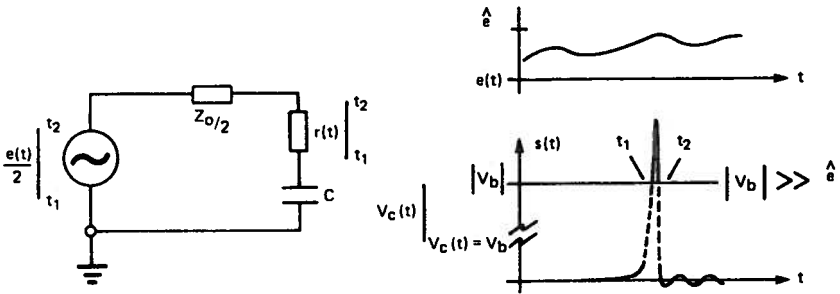


Fig 11 Sample gate switching action

When the sampling pulse amplitude exceeds  $|V_b|$ , the diode resistance becomes very small (compared to the reverse resistance) and the resulting current flow ( $t_1 \rightarrow t_2$ ) develops a voltage across  $C$ . This current is governed by the differential equation:-

$$\frac{e(t)}{2} = \frac{Z_o}{2} i(t) + r(t) i(t) + \frac{1}{C} \int i(t) dt \quad \dots (2)$$

The sampler output is the capacitor voltage change:-

$$y(\tau) = \frac{1}{C} \int_{t_1}^{t_2} i(t) dt \quad \dots (3)$$

Because this changes very little during the sampling period, it may be considered essentially constant and almost equal to  $V_c(t_1) = V_b$ . Equation (2) may thus be approximated by:-



$$e(t) - 2V_b = [Z_o + 2r(t)] i(t) \quad \dots\dots (4)$$

$$i(t) = \frac{e(t) - 2V_b}{Z_o + 2r(t)} = [e(t) - 2V_b] g(t) \quad \dots\dots (5)$$

Where  $g(t)$  is the gating function:-

$$g(t) = [Z_o + 2r(t)]^{-1} \quad \dots\dots (6)$$

Entering (5) in (3) now gives for the one sample  
sample ( $t_1 \rightarrow t_2$ ):-

$$y(\tau) = \frac{1}{C} \int_{t_1}^{t_2} [e(t) - 2V_b] g(t - \tau) dt \quad \dots\dots (7)$$

Where  $g(t)$  is synchronised to  $e(t)$  but delayed by a  
selectable time  $\tau$ .

$$\therefore y(\tau) = \frac{1}{C} \int_{t_1}^{t_2} e(t)g(t - \tau) + \frac{2V_b}{C} \int_{t_1}^{t_2} g(t - \tau) dt \quad \dots\dots (8)$$

Since the last term yields a constant:-

$$y(\tau) = K + \frac{1}{C} \int_{t_1}^{t_2} e(t) g(t - \tau) dt \quad \dots\dots (9)$$

This sampling function is thus of the integrated  
product type and in practice would be of a balanced form  
(ie two diodes at least). The constant term 'K' of  
equation (9) would thus be eliminated by the contribution  
of a second diode, capacitor and sample pulse as indicated  
in Fig 12. Sampling pulse leakage (kick-out) is also  
clearly balanced out by this circuit configuration.

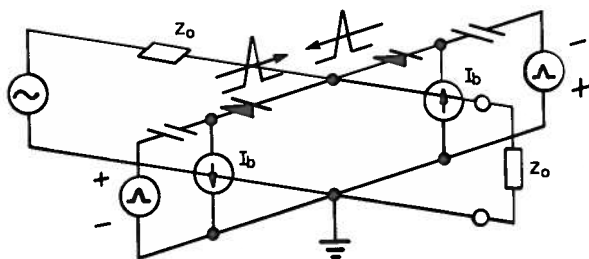


Fig 12 A two diode balanced sampling gate  
configuration

## 2.5 Sampler Probes.

A major problem in microwave measurements arises when we try to co-locate test equipment and the system under test. Obviously test leads and interconnections must be kept as short as possible to avoid waveform distortion due to cable/waveguide attenuation, phase and impedance mismatches. Sampling probes offer a novel means of achieving this objective.

Because the sampler may be constructed in a very small size, complete with pulse generator, it is ideally suited to probe type applications. Here the sampling diodes can be located at the back of a connector or probe tip (solder-in or touch) and present a well defined high frequency interface [36]. The output fed to the main body of the test equipment is then predominantly low frequency and has no influence on the measurement path.

## 3 VISUAL DISPLAY TECHNIQUES

Under this generic heading we can group not only sampling oscilloscopes, but correlators, time domain network analysers, sampling (down conversion) network analysers, sampling spectrum analysers, amplitude detectors and transient recorders [22]. Fortunately, most of these methods are being considered separately in other chapters of this book - whilst others only tenuously fall within the sampling system category. In this chapter we therefore concentrate on the single and multiple sampler oscilloscope.

### 3.1 The Sequential Sampling Oscilloscope.

In its conventional single sampler form this instrument synchronously sub-samples a waveform in a similar manner to that described in the previous Chapter, and more closely to that outlined by Yen [43] (Sampling with a Single Gap in an Otherwise Uniform Distribution). The physical realisation of this process requires a trigger signal [44-46] (generated external to the main CRO hardware and separate from the signal - or picked off within the CRO from the signal) to initiate regularly spaced samples relative to some fixed point in the signal. Each successive sample is delayed by a fixed amount  $\Delta t$  as depicted in Fig 13.

In practice there is normally a delay between the trigger signal and the samples being taken - this is due to the effective path length differences between signal and trigger. Whilst this is not usually a problem for waveforms of the kind shown it does sometimes create difficulties for pulse display, as will be explained later. The problem can be effectively overcome by the use of a delay line in the input signal path or by random sampling, as described in Section 3.2. Most commercial sampling CROs use samplers at a rate  $\sim 100$  kHz with a

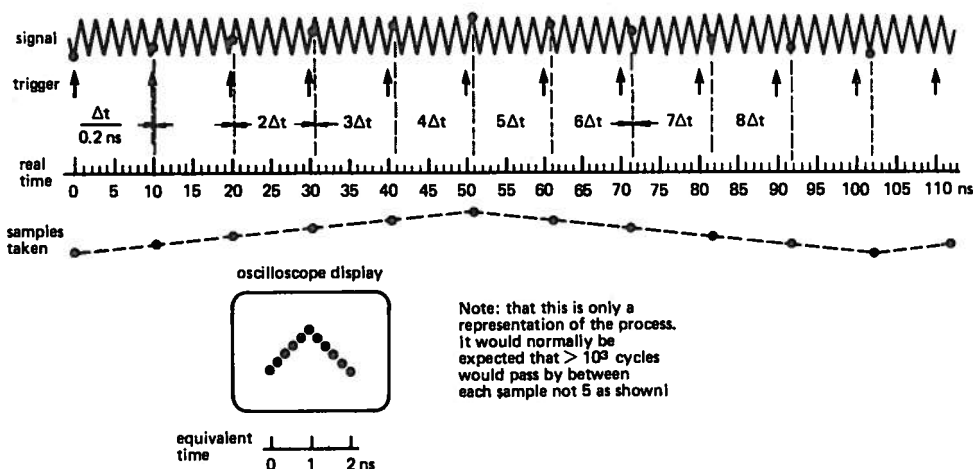


Fig 13 Sequential sampling and display of a periodic waveform

display of 1-3 k dots giving the illusion of a continuum - not as shown in the example. At this rate of sampling it can take  $\sim 1/50$  of a second to build up the display - just fast enough to avoid flicker.

Much of the sampling CRO hardware and its operation remains the same as its conventional real time counterpart, but as the sampling process is with reference to a particular point in the waveform, it is also capable of displaying repetitive but irregularly spaced pulses as shown in Fig 14.

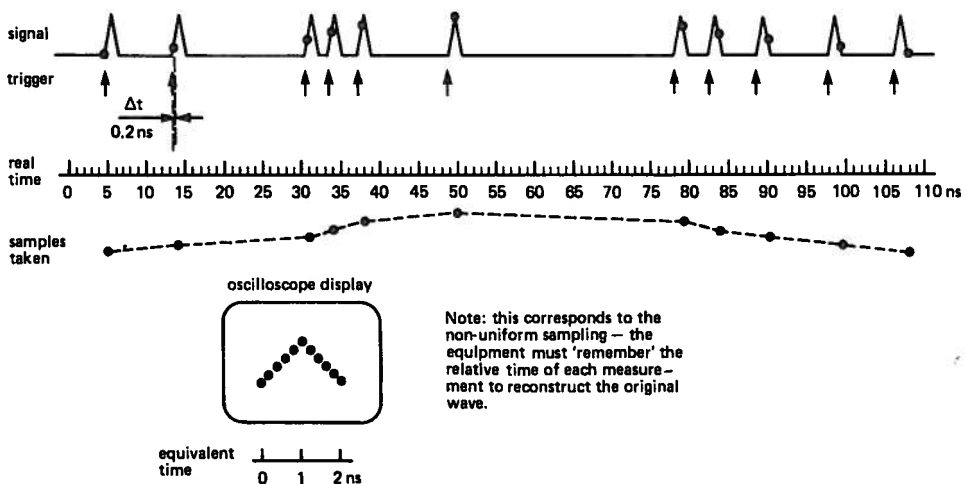


Fig 14 Sequential sampling and display of a repetitive but non periodic waveform

An indication of the hardware configuration and associated control waveforms of a commercial sampling CRO is given in Fig 15. The optional delay line in the input path to the sampler (shown dotted) overcomes the problem of initiating the trigger sample command prior to the arrival of a pulse at the sampler. However, unless this line is super-cooled [48,49] its bandwidth is unlikely to be more than 1 GHz or so! This is a severe limitation of the sequential sampling technique for pulse type applications, which fortunately, may be overcome without cryogenic plant as described in the next section.

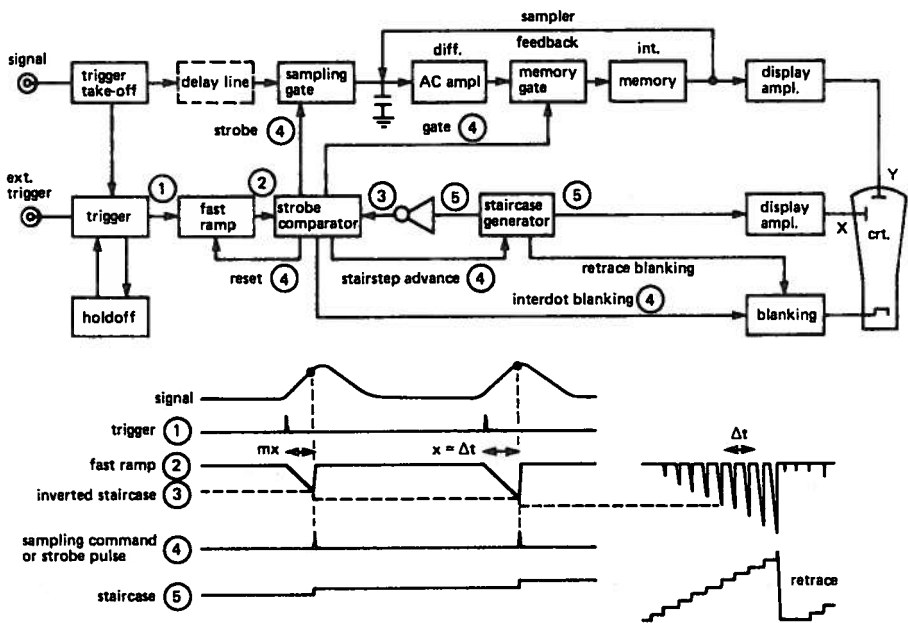


Fig 15 Schematic of a commercial sampling CRO

### 3.2 The Random (Display) Sampling Oscilloscope.

In the sequential case just described, the samples are taken in an orderly fashion one after another and displayed as a uniformly spaced succession of finely focussed spots. The distance between each spot thus represents a fixed interval in the original wave. For low repetition rate, or random arrival time pulses, this approach is inadequate as the first sample taken will miss the leading edge. This limitation is introduced by the different signal and trigger path delays within the CRO [45,46]. If the use of a delay line in the signal path cannot be tolerated, and if there is no external pre-trigger available, then we have to resort to a random sampling scheme.

The reader should note that; in most commercial equipments the word random does not imply truly random sampling or random pulse arrival times - indeed we are generally restricted to repetitive waveforms. The term arises from the randomisation of the final display due to processing uncertainties.

The principle behind this scheme is to trigger on one pulse and then delay the sampling action to just before the arrival of the next - thereby capturing the leading edge as well as the rest of the pulse using the sequential sampling routine previously described. The elements of a random sampling CRO are given in Fig 16.

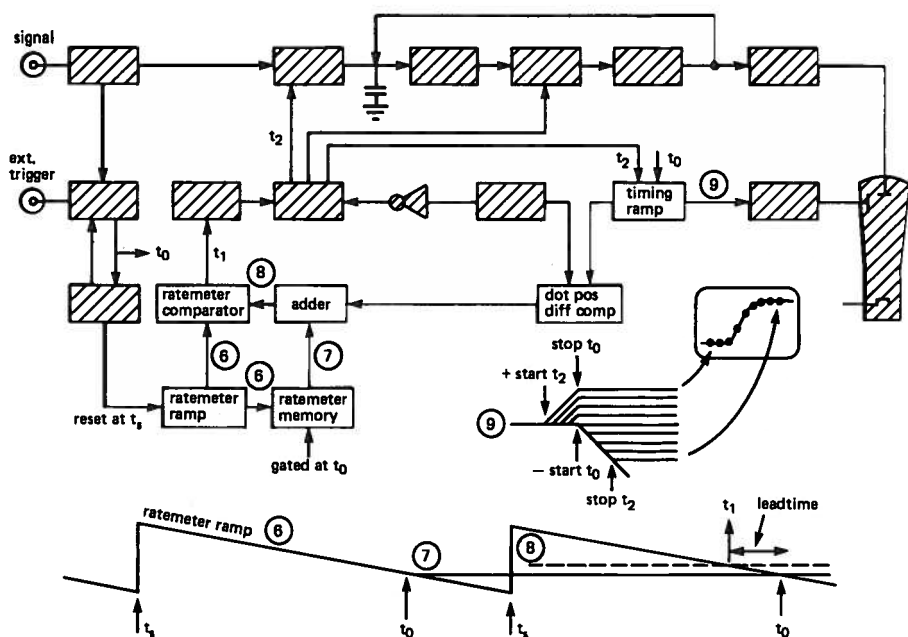


Fig 16 Schematic of a commercial "random sampling" CRO

Here key additional elements, over and above those shown in Fig 15, are shown unshaded. It should also be noticed that a number of interconnections have now been omitted and/or introduced between the new and existing blocks. The key element in this new configuration is the ratemeter which forms an estimate of the pulse repetition rate - and so positions the sampling window one (or more) pulse position/s on from the trigger point. This is achieved by initialising the slow ramp (6) shortly after

the trigger pulse (time  $t_s$ ) and then stopping the ramp at the next  $t_0$  (ie the same amplitude point in the pulse). The ratemeter memory then stores the amplitude (7) and a DC component is added (8) to create a sampling lead-time, allowing the whole of the pulse to be displayed and positioned mid-screen.

In principle this is a simple and effective scheme, but in practice there are some severe snags; any incidental noise, instability or FM on a signal continually changes the difference between successive pulse arrival times ( $t_0$ ) and thus the estimated sampling time ( $t_1$ ) also varies. In addition the ratemeter ramp can be extremely slow - and thus flat - thereby introducing switching point uncertainty at the comparator for (6) and (8). The sampling lead time can thus be subject to large uncertainties that would, if not corrected for, lead to an incoherent display. This limitation is overcome by the timing ramp which introduces an x-position correction (9) based on the difference between the sample position and trigger time. Display dots thus arrive on the screen in the correct position but not necessarily equispaced or in the correct sequence - leading to the description "random sampling".

### 3.3 The (True) Random Sampling Oscilloscope.

This scheme was devised [41] to record pulses of the same shape arriving in a random manner - specifically the condition of no synchronisation between signal and sampling [50]. For it to do this it has to record both amplitude and position information of each sample taken - see previous Chapter Sec 4. A schematic of the necessary hardware is given in Fig 17. Here it can be seen that the input pulse (1) and trigger (3) arrive simultaneously which triggers the X time ramp (7) at time  $t_0$ . A sampling pulse (2) arrives at some arbitrary time  $t_1$  and a sample is taken (4) and passed to the Y memory (5). The sampling pulse (2) passes through the delay (6) (allowing for the non-zero start up of the ramp generator) and stops the ramp (7) at time  $t_1 + \tau$ . The two memories now contain the initial information of sample amplitude and position which can be passed on to the CRT for  $\sim 3 \mu s$  of display, the memories are then reset for the next sample.

Although regularly spaced sample pulses (2) are shown, this is not necessary - random sampling pulses and random signal or periodic signal and random sampling can equally well be accommodated by this scheme. However, the principal mode of operation is likely to be preferred as this gives a higher likelihood of signal and sampling pulse being coincident. The arrival of the spots on the CRT are very definitely random for this instrument as illustrated by the examples of Fig 18 for N successive samples recorded.

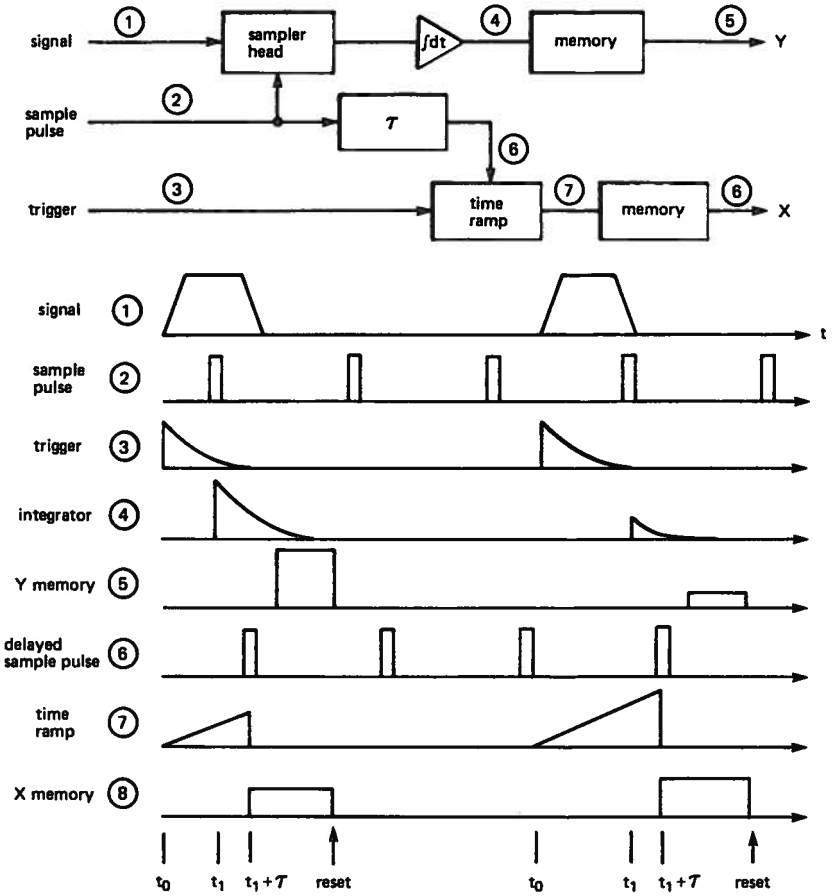


Fig 17 A true random sampling scheme

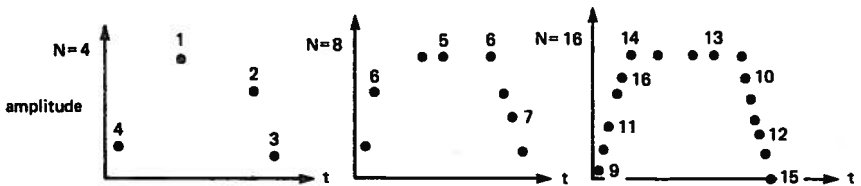


Fig 18 Random sample display assembly

### 3.4 The Digital Processing Oscilloscope (DPO).

A most powerful extension of the standard sampling CRO is now commercially available under the general title of the DPO [51]. This type of instrument is also reported in the literature under the heading of Time Domain Network Analyser [51]. Such equipments utilise A/D conversion of the CRO X and Y outputs (the X is now very often realised via a programmable delay as opposed to a time base ramp) to feed a signal processing computer. Here facilities such as Convolution, Deconvolution, FFT and IFT [54] may be used to manipulate recorded signals as described in previous chapters.

### 3.5 The Multiple Sampler Oscilloscope.

Unlike the CROs described so far, which function by time stretching - operating in equivalent time - the schemes we are now to consider operate in real time. Capturing a fast single shot event is extremely difficult at microwave frequencies, but has been achieved with a single sampler using a super-cooled recycling delay line and by using a multi-head sampling process [21,22,38].

In the recycling line case a pulse is injected into a super-cooled 'racetrack' [55] passing by a standard sub-sampler a number of times. At each pass a successively delayed sample is taken and a complete picture of the pulse recorded. Because the sampler has to operate at  $\mu\text{s}$  rates a long delay line is required that has to be super-cooled to avoid serious dispersion effects. This technique does not appear to have proved popular and is only scantily referenced.

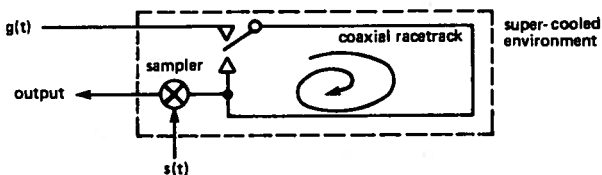


Fig 19 Racetrack multiple sampler

A more attractive arrangement, also scantily referenced is the multi-sampler solution [56,57] shown in Fig 20. Here tens, and sometimes hundreds of samplers, are arranged along a relatively short line; a 10 ps sample spacing dictates  $\sim 3$  mm between each head, whilst 100 ps requires  $\sim 3$  cm. Thus for 100 samplers the line only need be  $\sim 0.3$ -3 m long. These present a wide real time sampling window to a pulse which may be captured at a single shot.

A/D conversion or direct readout and display may follow the multi-head sampling operation - as per the more popular single sampler CRO previously described.



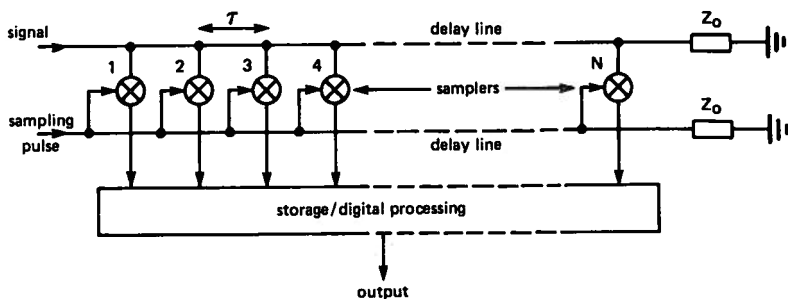


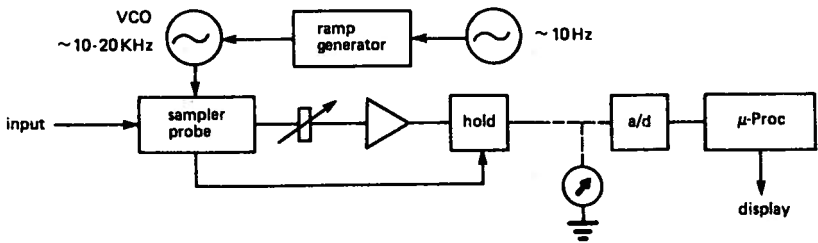
Fig 20 Multi-sample gate solution

#### 4 PARAMETRIC MEASUREMENT TECHNIQUES

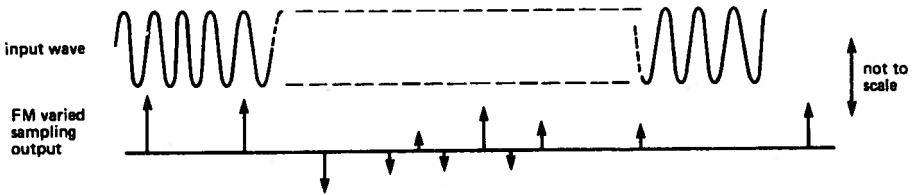
There are a very large number of techniques that fall under the general heading of this section. These use random or synchronised sub and super-sampling to perform time domain processing and frequency domain down conversion [36]. We therefore consider some of the more common, and mention some not so common, examples of these types of processes.

##### 4.1 Random Sampling Voltmeter.

Producing detectors (ac to dc converters) for microwave applications is extremely difficult if wide dynamic range and flat frequency response are required. Generally, semiconductor diodes change their mode of operation with signal amplitude and frequency [58]. For example; the exponential characteristic of a diode dictates that it tends to be a good peak detector for sinusoidal signals of  $\geq 500$  mV amplitude and gives an rms value for  $\leq 30$  mV. In addition, the stray L, C associated with both the diodes and their mounts also render them frequency sensitive. Such limitations obviously become further compounded for non-sinusoidal and modulated signals. These factors coupled with the temperature sensitivity and inherently noisy characteristics of such detectors precludes their general use in microwave measurements. Fortunately all of these limitations can (largely) be overcome by the use of a sub-sampling voltmeter [59]. The schematic of a typical instrument is given in Fig 21(a). Instruments of this type rely on a large number of samples taken at random in the wave to allow such parameters as the; peak, mean, rms, power and in some cases the pdf to be recorded. Randomisation of the sampling process is necessary for the reasons stated in the previous Chapter, and in this particular scheme is achieved by frequency modulating the sampling rate. A typical sampling frequency would be 10-20 kHz modulated at 10 Hz as depicted in Fig 21(b). Alternatively a noise source of pseudo-random modulation sequence may equally well be employed.



(a)



(b)

Fig 21 (a) Random sampling voltmeter  
(b) Randomised sampling

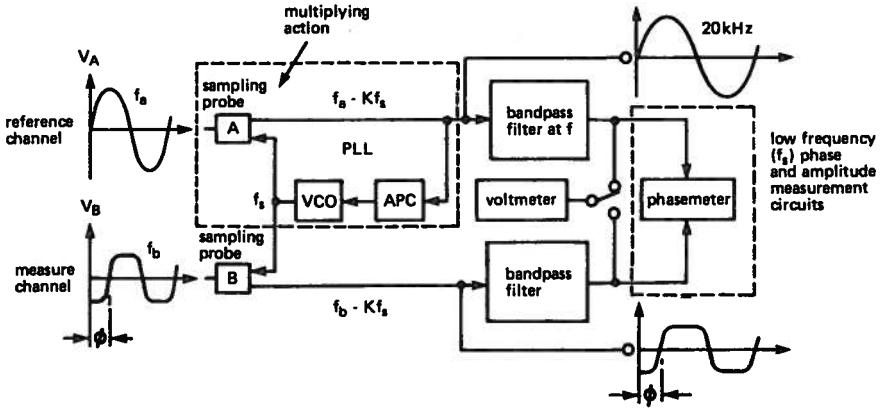
Instruments based on this scheme are principally limited by the type of sampler used, but can be expected to yield:-

Sensitivity	< 50 $\mu\text{v}$
Resolution	< 20 $\mu\text{v}$
Accuracy	+ 3%
Convergence (after autoranging)	< 2 seconds

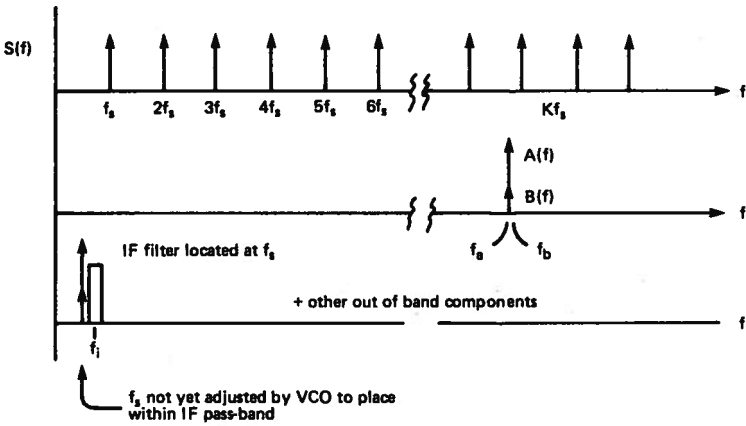
#### 4.2 Phase Locked Sampling Vector Voltmeter.

In this type of instrument the wideband sampler is effectively used to down convert a signal to a pre-defined Intermediate Frequency (IF) [60]. This is achieved by synchronous sub-sampling controlled by a Phase Locked Loop (PLL) circuit as indicated in Fig 22.

Because the samplers produce a comb-like spectrum over a very wide range, the incoming signal is convolved onto the spectral lines to create a low frequency component that lies within the pass-band of the IF filters. When a signal is initially applied to reference channel 'A' and the PLL is not locked, the modulation components may not fall within the pass-band centred on  $f_s$ . The PLL search generator (Fig 23) produces a ramp which sweeps the sampling VCO; when the modulation component moves into the IF filter range the PLL locks and the search sweep is inhibited. Under this condition the difference between the Kth harmonic of  $f_s$  and  $f_a$  is  $f_i$ .



(a)



(b)

Fig 22 Phase locked vector voltmeter

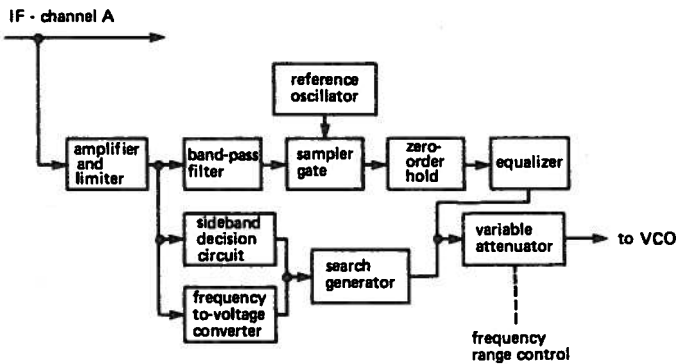


Fig 23 Phase lock search generator

Commercial instruments [61] typically use  $\sim 20$  kHz sampling rates with IF bandwidth  $\sim 1$  kHz and exhibit  $>90$  dB dynamic range. This is mainly afforded by the noise reduction performance of the narrow-band IF, which also allows precision amplitude and phase measurements to be made with relatively modest hardware following the IF filters. Typical performance figures are 0.1 dB and  $0.1^\circ$  resolution.

#### 4.3 Phase Locked Sampling Frequency Meter.

As described in Section 3.2 of the previous Chapter, any sub-sampling system inherently implies a frequency down conversion process [60]. Provided sufficient information about the signal being measured is available, then it follows that its frequency may be recorded using a low frequency counter. However, such information - necessary to perform measurements on the correct spectral line - is not generally available without some sophisticated pre and post-sampler processing [60-63]. One scheme that gives the correct frequency scaling - or spectral line selection - automatically [64] is shown in Fig 24.

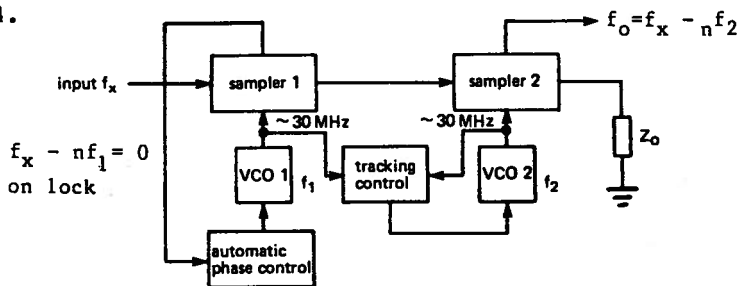


Fig 24 Automatic phase locked sampling frequency meter

The two feed-through samplers (as described in Section 2) are operated at different sampling rates,  $f_1$  and  $f_2$ , which are known with precision. This is achieved by the frequency offset PLL arrangement of Fig 25.

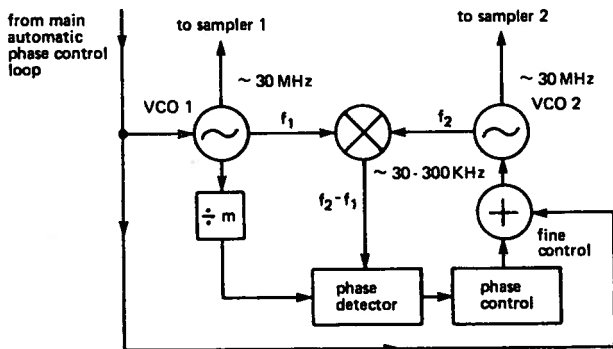


Fig 25 Offset PLL sampling clock generator

In turn the two samplers are phase locked to the unknown frequency such that:-

$$f_x = nf_1 \quad \dots\dots (10)$$

$$\text{and} \quad f_o = n(f_1 - f_2) = nf_1 \left( 1 - \frac{f_2}{f_1} \right) \quad \dots\dots (11)$$

$$\text{but} \quad \frac{f_1}{m} = f_2 - f_1 \quad \dots\dots (12)$$

$$\therefore \quad \frac{f_2}{f_1} = \frac{m+1}{m} \quad \dots\dots (13)$$

$$\text{so} \quad f_o = \frac{f_x}{m} \quad \dots\dots (14)$$

The value of 'm' is usually  $10^2$ - $10^4$  and counting the frequency is therefore straightforward - even at 20-40 GHz. This approach overcomes many of the limitations and spectral line uncertainties of prescalers using mixers and IF amplifiers [65]. However, with no front-end protection for the first sampler the PLL design becomes more difficult as this has to cope with a range of input levels - which can be adversely affected. The two main requirements of the input PLL are:-

- i. An automatic search capability - usually achieved by a ramp sweep of the VCO - disabled on acquisition.
- ii. A wide gain margin to maintain loop stability over a wide range of harmonic numbers;  $n = 10$ -500.

A good description of this design problem is given by Allen [64] and a more complex alternative using triple parallel sampling is described by Aitchison [63].

## 5 A FINAL NOTE ON SYSTEMS

In this Chapter we have briefly looked at the design, realisation and operation of samplers, and their application in a few instruments concerned with display and parametric measurement. Although we have cited numerous references and made comment on these, it should not be supposed that the coverage is comprehensive - for it is not! We have merely taken a snap-shot (a sample!) of what is available in the published literature - when this contribution was researched more than 400 pertinent references were found - with relative ease!

Where next - what does the future hold? Remarkable as it might seem we can expect even faster commercial samplers based on quantum and optical devices that should break the 1 ps barrier. Even more powerful and compact computers will also become available in the near future to give higher degrees of sophistication in the related signal processing and measurement control.

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## 7 REFERENCES

1. Janssen, J.M.: 1950, Philips Tech Rev, 12, 52-81.
2. Germeshausen, K.J., Golderberg, S. & McDonald, D.F.: 1957, Trans IRE, ED-4, 152-158.
3. Frye, G.J., Bruce, J.D. & Nahman, N.S.: 1961, Trans IRE, 1/10, 85-89.
4. Bradley, D.J. & New, G.H.C.: 1974, Proc IEE, 62, 313-345.
5. Clement, G. & Loty, C.: 1973, Electron, 16/1, 102-111.
6. Prosser, R.D.: 1972, Proc IEEE, 60, 645-646.
7. Stonebaker, D.M.: 1968, NBS Jnl, 72/2.
8. Andrews, J.R. & Nahman, N.S.: 1971, IEEE 11th Symp on Electron, Ion and Laser Beam Technology, San Francisco Press Inc, 141-146.
9. Bologlu, A. & Barber, V.A.: 1978, HP Jnl, 2-16.

10. Schneider, R.F., Felenstein, R.E. & Offermann, R.W.: 1979, HP Jnl, 41-47.
11. Cole, R.H.: 1982, IEEE Conf on Precision Electromagnetic Meas C/18-20.
12. Faulkner, N.D. & Vilar, E.: 1982, ibid M/10-11.
13. Sampling: 1982, A key to the future in hyperfrequency instrumentation. Toute Electron, 470, 23-5.
14. Malherbe, J.C. & Kirilenko, J.F.: 1981, Electron Indust, 8, 45-7.
15. Perrett, J.J.: 1981, ibid 19, 53-4.
16. Anderson, J.M.: 1980, Rev of Sci Inst, 52/1, 145-146.
17. Cittins, D.R.: 1979, Comm Int, 6/1, 48-50.
18. Fujisawa, K., Yamamoto, Y., Ito, T. & Iwai, T.: 1978, 8th European Microwave Conf, 508-512.
19. Gaddy, O.L.: 1960, IRE Trans Inst 1/9, 326-333.
20. Honnold, G.H. & Nahman, N.S.: 1964, IEEE Trans Inst and Meas, 123-128.
21. Nahman, N.S.: 1967, Proc IEEE, 55/6, 855-864.
22. Nahman, N.S.: 1978, Proc IEEE, 66/4, 441-454.
23. Nahman, N.S.: 1983, IEEE Trans, IM-32/1, 117-124.
24. Andrews, J.R.: 1973, Trans IEEE, IM-22/4, 375-381.
25. Tieler, R.: 1976, IEE Elec Lett, 12/3, 84-85.
26. Pulse and waveform generation with step recovery diodes. HP Appl Note 918.
27. Andrews, J.R. & Baldwin, E.E.: 1978, NBS Tech Note 888.
28. Tuckerman, D.B.: 1980, App Phys Lett, 36/12, 1008-1010.
29. Weker, N.K. & Bedard, F.D.: 1977, URSI Conf on Meas in Telecomm, Lannion, 155-158.
30. Faris, S.M.: 1980, App Phys Lett, 36/12, 1005-1007.
31. Hohkawa, K., et al: 1983, Elect Lett, 19/8, 291-292.

32. Grove, W.M.: 1966, IEEE Trans, MTT-14/12, 629-635.
33. Sternes, K.J.: 1972, IEEE Trans, IM-21/3, 209-214.
34. Ramo, S., Whinner, J.R. & Van Du Zer, T.: 1965 Fields and Waves in Communication Electronics. John Wiley, 463.
35. Riad, S.M.: 1982, IEEE Trans, IM-31/2, 110-115.
36. Sayed, M.M.: 1980, HP Jnl, 31/4.
37. Mulvey, J.: 1970 Sampling oscilloscopes. Tektronix, Beaverton, Oregon.
38. Tektronix: S-6 sampling head. ibid.
39. Sugarman, R.: 1957, Rev of Sci Inst, 28/11, 933-938.
40. Grove, W.M.: 1966 12.4 GHz Feedthrough Sampler HP Jnl.
41. Nahman, N.S. & Riad, S.M.: 1978, IEEE Microwave Symposium Digest, Ottawa, 267-269.
42. Nahman, N.S.: The Characteristics of Sampling. Lecture notes for a joint University of Colorado/NBS course on "Time Domain Measurements" Spring Semester 1976 and also reproduced for Ecole d'Ete Tegor, CNET, Lannion 1978.
43. Yen, J.L.: 1956, IRE Trans on Cct Theory, 251-257.
44. Best, A.I., Howard, D.L. & Umphrey, J.M.: 1966, HP Jnl 27/3.
45. Tektronix: 7S11 Sampling Unit Manual. Tektronix, Beaverton, Oregon.
46. Tektronix: 7T11 Sampling Sweep Unit. ibid.
47. Lawton, R.A. & Andrews, J.P.: 1976, IEEE Trans, 25/1, 56-60.
48. Nahman, N.S.: 1973, Proc IEEE, 61/1, 76-79.
49. Andrews, J.R.: 1974, IEEE Trans, IM-23/4, 468-472.
50. Frye, G.J. & Nahman, N.S.: 1964, IEEE Trans IM-13/1, 8-13.
51. Rousseau, T. & Cox, B.: 1980, Tekscope, 12/3, 3-9.
52. Bancroft, J. & Johnston, R.: 1973, Proc IEEE, 20/1, 472-473.
53. Andrews, J.R.: 1978, Proc IEEE, 66, 414-423.



54. Gans, W.L.: 1976, IEEE Trans IM-25, 384-388.
55. Cummings, A.J. & Wilson, A.R.: 1964, Proc IEEE, 52, 1749.
56. Schwarte, R.: 1972, Elec Lett, 8/4, 95-96.
57. Davies, T.J. & Nelson, M.A.: 1976, Applied Optics, 15/6, 1404-1410.
58. Detwiller, W.L.: 1979, Communications, 16/2, 42-48.
59. Boatwright, J.T.: 1966, HP Jnl, 17/11, 2-8.
60. Yen, C.S.: 1965, IEEE Trans, IM14/1, 64-68.
61. Carlson, R. & Weinert, F.K.: 1966, HP Jnl.
62. De Bella, G.B.: 1968, HP Jnl.
63. Underhill, M.J., Sarhadi, M. & Aitchison, C.S.: 1978, IEE Elec Lett, 14/12, 366-367.
64. Allen, R.L.: 1967, HP Jnl.
65. Chappel, R.: 1978, Electronic Eng, 39-43.

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