Applications of RF and Microwave Sampling to Instrumentation and Measurement

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Abstract — **Measurement of microwave and UHF signals is often done with sampling techniques. In this review, the techniques and technology of sampling of electrical signals is reviewed from the beginning of the twentieth century to the present. It includes both references to the open literature as well as an extensive review of relevant patents. This review is specifically oriented toward applications and not theory. It was written to introduce the Special Session on "High Speed Sampling Circuits and Techniques" at IMS 2003.**

I. Introduction

The design and construction of apparatus to view and contemplate the time varying behavior of electrical waveforms has been a long standing activity dating back to the 19th century. (see Phillips' book[1] for the early history of oscillography). The evolution of electrical and electronic technology has made it possible to see and analyze signals of increasingly high frequencies Starting in the 1940s, the increased interest in microwave signals and systems, motivated particularly by Radar (see Buderi's thrilling account of Radar development[2]), necessitated the development of high frequency instrumentation.

This review places the improvement in technology in context with the circuits used by RF samplers in microwave instrumentation.

II. Early instruments: Before 1959

As early as 1904, Hospitalier[3] described a mechanical sample and hold oscillograph [1] This "ondograph" (wave recorder) is pictured in Fig. 1. The ondograph used a revolving mechanical switch to charge a capacitor from the input waveform. The capacitor was discharged into a coil that moved a pen on paper. This simple but effective method permitted the illustration of waveforms for almost 50 years.

In 1940 two patents were filed by General Electric covering early sampling oscilloscopes[4], [5]. As can be seen in 2 from Norgaard's patent, a linear sweep of pulses gates the grid of the CRT, thereby displaying short portions of the input waveform. Accordingly, his patent specifies that the input can be mixed or heterodyned; further, the sweep oscillator must be synchronized with the input waveform. Unfortunately, no further details of implementation were mentioned in the patent.

[1] Hospitalier gives credit for the "point method" to M. Joubert

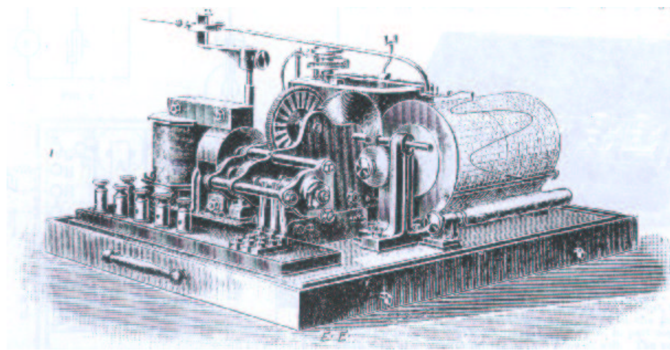

Fig. 1. Hospitalier's ondograph[3]

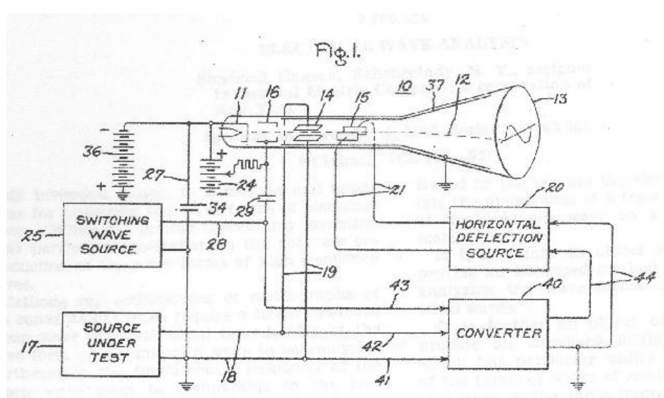

Fig. 2. Early GE patent figure[4], [5]

III. Applications

While not attempting to be exhaustive, this section reviews some of the applications of sampling to measurement and instrumentation. A recent review[6] examines oscilloscope developments in detail while Cochrane has an older review of sampling applications[7].

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A. Sampling Voltmeters

Sampling voltmeters date back at least to Spencer's patent[8]. As shown in Fig. 3, a sampling bridge output is filtered and delivered to a (Vacuum Tube Volt) meter.

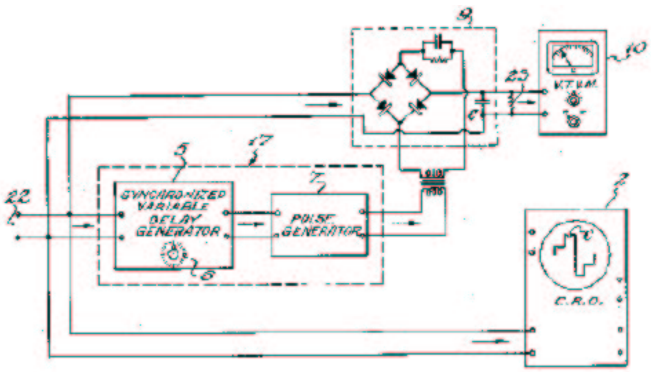

Fig. 3. Spencer's sampling voltmeter[8]

In 1965, Yen[9] described the principles of the 8405 Vector Voltmeter[10]. The principal achievement was the use of a phase lock loop to tune the local oscillator so that the alias (IF) band is aligned with the phasemeter passband. The block diagram is shown in Fig. 4.

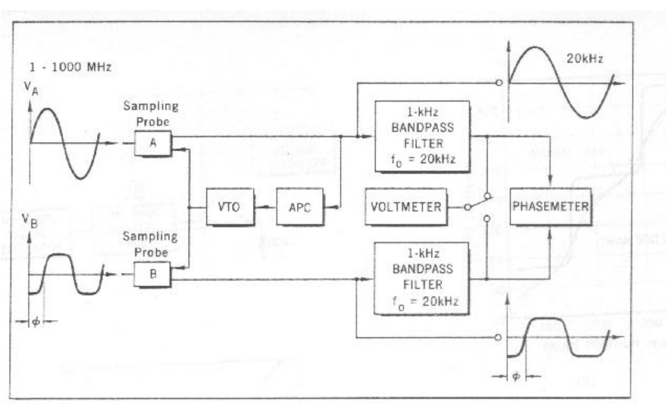

Fig. 4. Block diagram of the HP 8405 vector voltmeter[10]

The sample and hold output of the sampler is given to a bandpass filter and then a phase comparator that compares it against a reference oscillator. The output of the phase comparator is filtered and output as the control voltage of a Voltage Tuned Oscillator (VTO). The VTO in turn generates the sampling pulses through use of a Step Recovery Diode (SRD). This basic concept will also find application in the HP 8410 Vector Network Analyzer (see section III-B).

In 1966, H-P introduced the model 3406A Broadband Sampling Voltmeter[11], [12]. This high frequency (> 1.2 GHz) scalar voltmeter used a four diode switch in the probe pulsed by a variable 10 kHz to 20 kHz oscillator. This avoids the many beat frequencies of the input waveform. This "incoherent sampling" method is *not* in phase with the input frequency. However, the RMS values, peak values and averages are still valid over the long term.

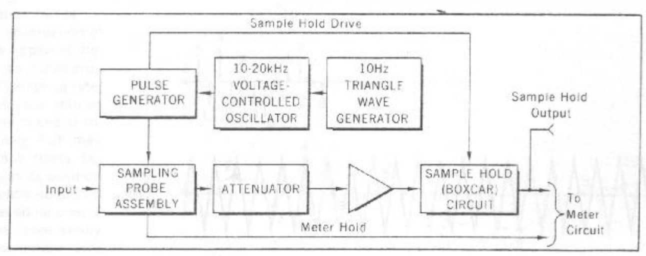

Fig. 5. Block diagram of the HP 3406[11], [12]

McCracken[13] described a phase-sampling voltmeter for repetitive waveforms that permits amplitude measurements at any point on the waveform by adjusting the delay of the sampling gate trigger from the trigger point. In 1988, Gärtner and Schiek[14] analyzed the error sources of RF vector voltmeters and also proposed a self-calibration procedure. Mirri, *et al.*[15] proposed combining randomized sampling with a vector voltmeter. In the final implementation[16], they used three samplers with differing trigger times.

B. Network Analyzers

In 1967, HP introduced the model 8410 network analyzer[17] which revolutionized the measurement of scattering parameters. An important component of the 8410 system was the 8411A "Harmonic Converter". It used the same sampler as the 1430 and 1431 sampler described by Grove[18]. The samplers were driven by a harmonic generator (via a SRD driven by a VCO) instead of the sampling pulse generator.

The use of a samplers in network analyzers results in $\frac{\sin x}{x}$ distortion due to the on-off behavior of the sampling switch. By biasing the sampling diodes appropriately[19], the distortion can be ameliorated without resorting to trying to control the pulse width from the Step Recovery Diodes. Additionally, the wrong subharmonic (alias) can be locked onto by the network analyzer phase lock loop. This "false lock" can be resolved by carefully choosing the IF frequency[20], [21].

Conway, *et al.*[22] used a distributed sampler in their frequency converter, amplified the output of the sampling gate and injected it into a delay line with a *slower* delay between sampling points.

Bose and Courteau[23], [24] used a DSP to do the synchronous conversion rather than the analog circuitry of the 8410 and its follow-on, the 8510 [25]. The Wiltron 360[26] also uses digital techniques.

Since measurement of nonlinear devices is problematic on Network Analyzers, Kompa, *et al.*[27] used a network analyzer to measure magnitude and phase and a sampling oscilloscope to measure time dependent behavior. Sipilä, *et al.*[28] describe a sampling oscilloscope based measurement system that specifically measures nonlinear devices but it suffered above 5 GHz due to the “trigger drift”.

Time Domain Network Analysis (TDNA) was originally proposed and developed by Nicolson[29], [30] and was fully developed by NBS[31], [32]. NBS digitized a HP 140 series sampling oscilloscope to compute the frequency response from the time domain data and then compute scattering parameters. This project was reviewed by Andrews in 1978[33].

C. Microwave counters

It is also important to measure frequency stability in the microwave region. Accordingly, RF sampling has been used as a critical component of many microwave counters. Samplers are used in *transfer oscillators*, where an oscillator is phase locked to the input waveform and in *harmonic heterodyne* counters, where the sampling gate is given a carefully controlled synthesized IF.

In “subharmonic sampling”, a reference oscillator is used to control the pulse generator that strobes the sampling gate. The result is now called “subsampling”, i.e., the aliases are spread up and down the spectrum. A bandpass filter can be positioned to extract the signal information.

The Hewlett-Packard 5340A[34] used a transfer oscillator technique with a new thin film gate designed by Merkelo[35], [36]. Essentially, it is a technological update of Grove’s sampler — the beam lead diodes are connected to a slotline. The VSWR was only 1.7 over a broad frequency range. This sampling gate was also used as the input gate to the HP 5342A counter.

The 5340A used two samplers which resulted in a high cost instrument. Chu[37] described a single oscillator transfer oscillator that simplifies the system considerably.

Unfortunately, the harmonic heterodyne technique requires searching for the proper harmonic because downsampling creates multiple aliases (subharmonics). Using multiple samplers, Underhill, *et al.* [38] proposed constraining the search via subband intersection. Peregrino and Throne[39] patented a correlation method of computing the harmonic number. Peregrino[40] describes a linear programming solution to reducing the search time.

The HP 5350/1/2A counter[41] uses an update of Merkelo’s sampler to implement a harmonic heterodyne counter. The new sampler used a thin-film hybrid that includes a two diode GaAs sampling gate chip together with a Step Recovery Diode pulse generator.

Faulkner and Mestre[42] describe the use of avalanche transistor pulse generator and two diode sampler to measure stability of oscillators by downsampling the microwave input.

D. Time Domain Reflectometry

Given the unreliable nature of cable, many instruments have been designed to find discontinuities in transmission lines. The first use of sampling must be Dévot’s early TDR[43] shown in Fig. 6. A pulse is transmitted down the transmission line and is received and displayed directly on the vertical plate of the CRT.

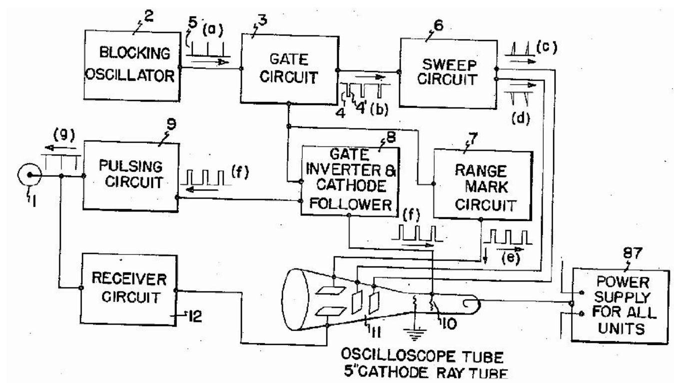

Fig. 6. Dévot’s Time Domain Reflectometer[43]

Bauer[44] explicitly invokes the “stroboscopic sampling” gate in his 1966 patent (filed in 1962). Oliver’s paper in the HP Journal[45] can be seen as the preface for the the 1415A plug-in[46] for the 140A oscilloscope mainframe.

Frye at Tektronix introduced a TDR that didn’t need a hybrid at the receive/transmit junction[47]. He used a tunnel diode as the pulsed current source. Tektronix[48] patented a form of “baseline correction” that compensates for pulse generator bias. Another Tektronix patent[49] illustrates how to use a single SRD pulser to drive two sampling gates in a two channel system.

E. Switching and settling time measurement

Measuring settling time (e.g., of Digital to Analog Converters) is difficult because of the large swing and resulting amplifier overload. Sampling offers a unique advantage since it captures the input voltage before (typically) undergoing amplification. The model 186A “switching time tester”[50] plug-in for the 185A mainframe included two bias supplies, a fast pulse generator and a four diode bridge sampling gate. NIST built a sampling bridge for the measurement of settling time[51]. They later designed a custom comparator for the same task[52]. Burr-Brown[53], [54] designed a sampling digitizer for specific use in measuring settling time. Williams[55] describes the difficulty of measuring settling time to 16 bit accuracy. [2]

[2]He also prefers his Tektronix 661 for the task

IV. CONCLUSION

For low frequency microwave signals fast A/D converters have replaced the use of samplers (particularly in digital oscilloscopes). However, there's nothing quite like a sampler for high input frequencies. Given the current state of the art, we can expect to see samplers in instrumentation for many years to come.

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