# Applications of RF and Microwave Sampling to Instrumentation and Measurement

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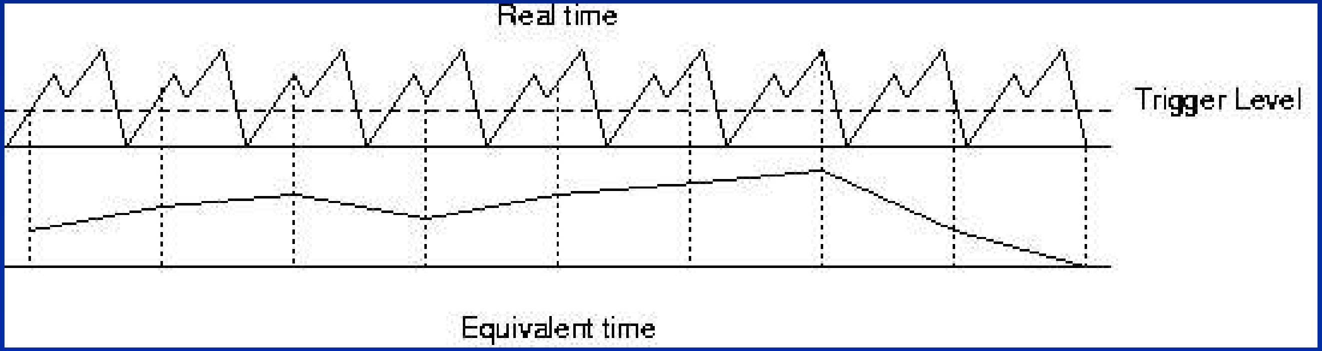
# Talk outline

- Sampling principles & tradeoffs
- Applications
  - Oscillography
  - Sampling Voltmeters
  - Network Analyzers
  - Microwave Counters
  - Time Domain Reflectometry
  - Computer assisted measurements
- Future directions
- Conclusion

# Why sample?

- Problem: Input exceeds instrument limitations
  - 40 Gbit/s optical fiber transmission
  - 60 GHz wireless LANs
  - ~5-8 picosecond pulse rise times
  - 150-200 GHz $f_{max}$ in front end circuits
- Solution: Downsample to lower frequency
  - Fast sample and hold



# Sampling Principles & Tradeoffs

## *Principles*

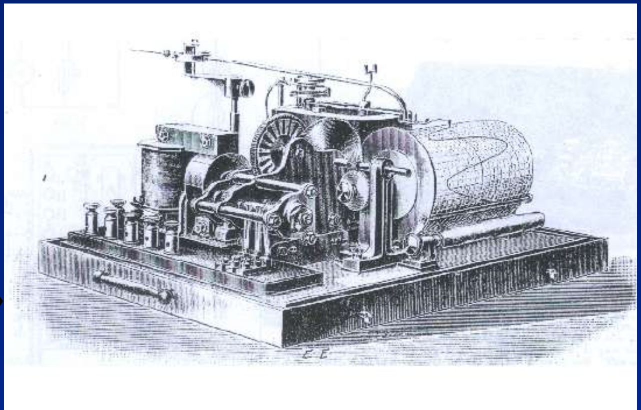
1. Input waveform is repetitive
2. Fast switch (gate) charges a capacitor
3. Gate is *strobed* by a narrow pulse
4. Strobe trigger is generated by the time base

## *Tradeoffs*

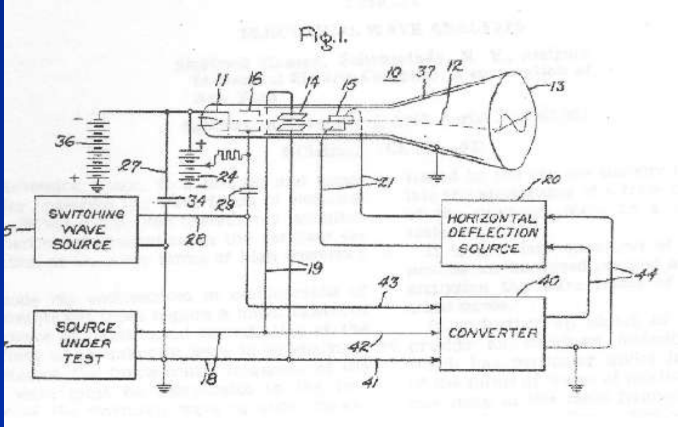
1. Input circuitry affects waveform shape
2. Gate (aperture) time is not instantaneous
3. Strobe waveform is not a perfect $\delta$
4. Time base has drift and jitter

# Early pre-history (pre 1950s)

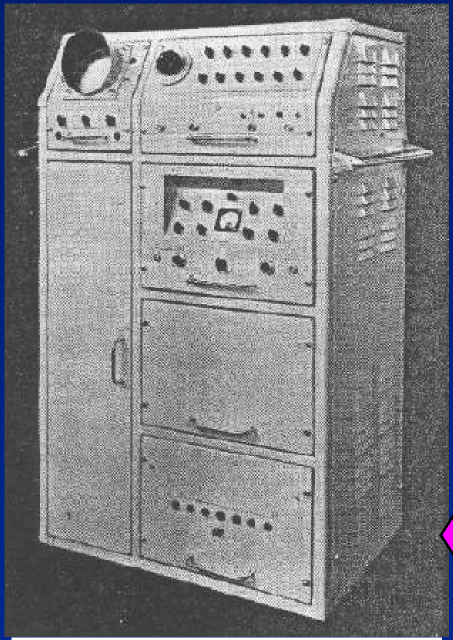
- Hospitalier (1904) *Ondograph*
  - revolving mechanical switch charges a condensor
  - discharged into a coil that moves the pen



- Norgaard & Hansen (1940)
  - linear sweep gates the grid of the CRT
  - input can be mixed or heterodyned



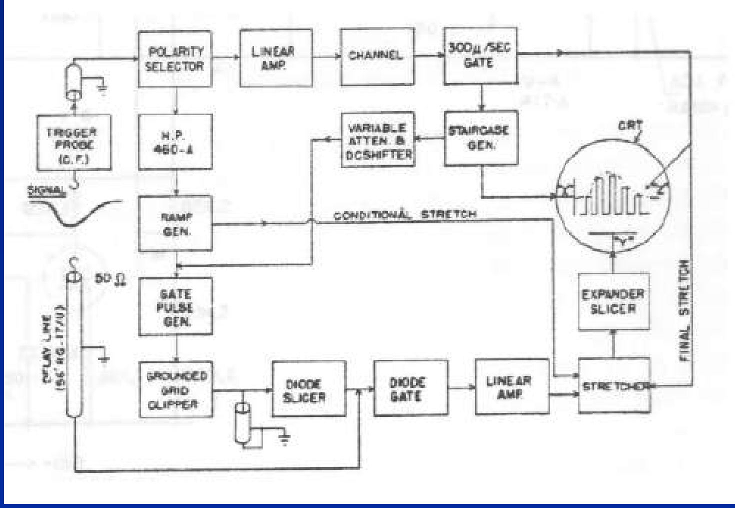
# Oscillography: Early history (1950s)



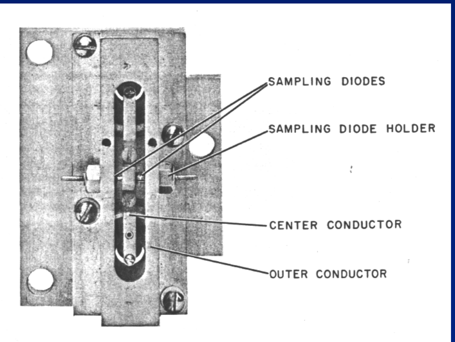
*Technological Improvements*

- *Faster gates*
- *Faster strobes*
- *Better dynamic range*

- Janssen (Philips, 1950)
- McQueen (1952)
- Sugarman (1957)
- Chaplin (1959)
- Reeves (1959)

# Oscillography: Commercial Introduction (1960s)




The instrument ... combines great bandwidth and high sensitivity with basic ease and simplicity of operation. It is in every sense of the word a general purpose instrument.

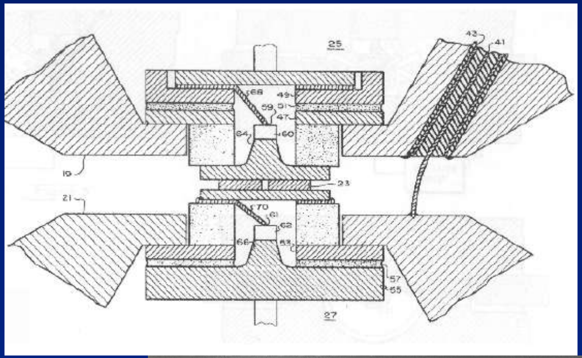
(W. R. Hewlett, 1960, HP Journal)

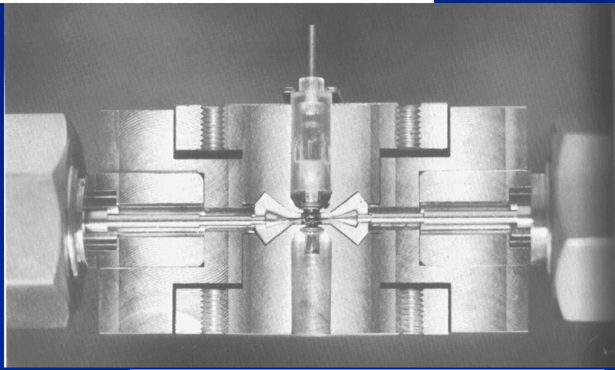
***Technological Improvements***

- *Faster gates*
- *Faster strobes*
- *Better triggering*
- *Better sweep control*

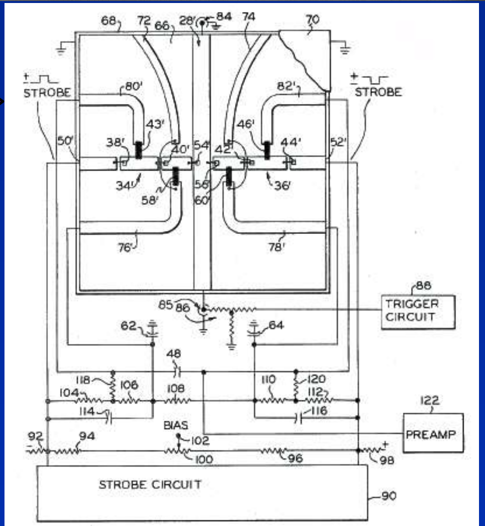

- Lumatron
- HP 185A + 187A + 188A
- Tektronix type N (500 series plugin)
- Tektronix 661 + 4S + 5T

# Oscillography: Technology improvement (1960s)





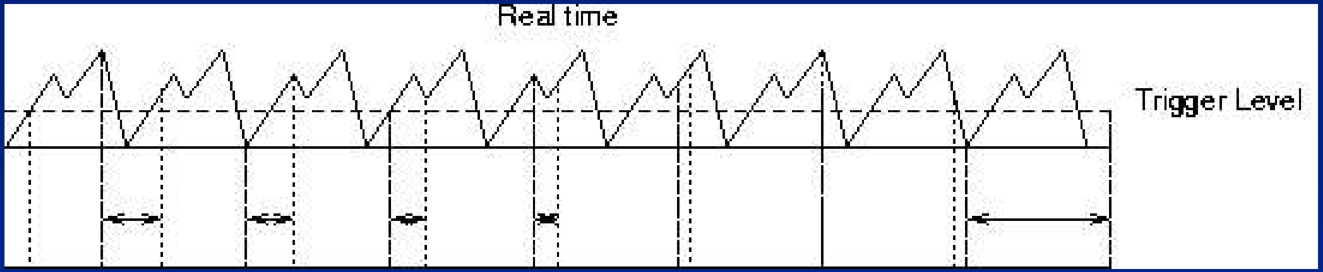
- HP 1411A/143x (140 mainframes)
  - New 2 diode sampler (12.4 GHz) (Grove, 1965)
  - Used extensively by NBS for TDNA
- Tektronix 1S series (500 mainframes)
  - 1S1 (1965)
  - 1S2 TDR unit (1967)
- Tektronix 3S + 3T series (560 mainframes)
  - S4 traveling wave sampler (Frye, 1968)
  - 3T2 random sampling time base



# Random sampling

**Problem: Trigger delay line distorts**

**Solution: Use time interval measurement**

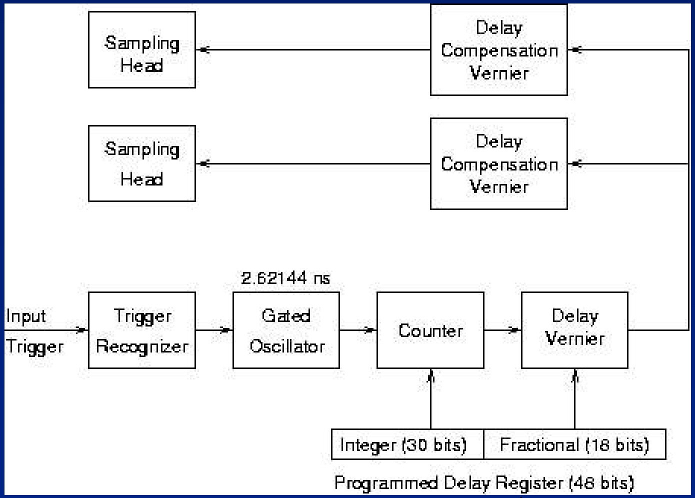



- Nahman and Frye (1964)
  - Move delay from vertical input to time base
- Horňák (1965, 1969)
  - Horizontal position derived from separate time base
- Frye (Tektronix, 1973) 3T2 & 7T11
  - Combined random/equivalent time

# Oscillography: Technology Improvement

- *Gate designs*
  - Sampling bridge asymmetry (Benson, 1971)
  - Better trigger pickoff (Lockwood, 1971)
  - Dual samplers for TDR & VNA
  (Agoston, et al., 1986; Bradley, 1996)
  - High impedance input (MESFET)
  - Josephson junctions (Hamilton, et al., 1979)
- *Blowby:* Transmission of high freq. inputs through the open gate
  - Circuit improvements: balanced gates, compensation networks
  - Traveling wave gate bias control (Agoston, 1986)
- *Kickout:* Feed-through of strobe to input connector
  - Insert isolator in front of gate

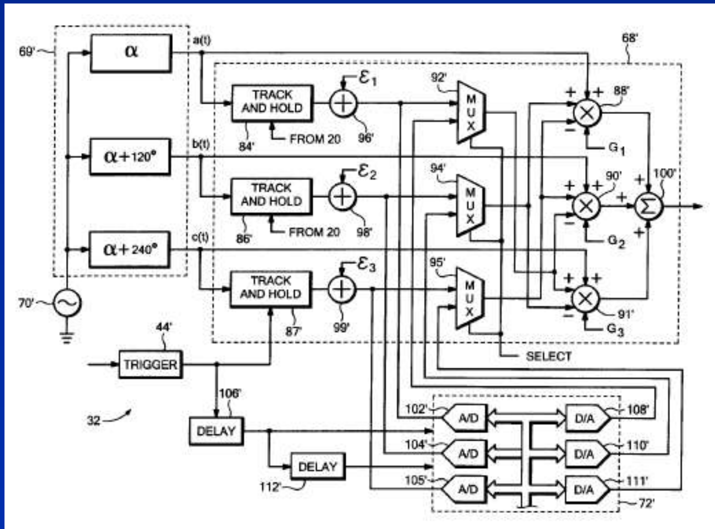
# Oscillography: Time bases




## Problem: Analog nonlinearities

## Solution: Digital control

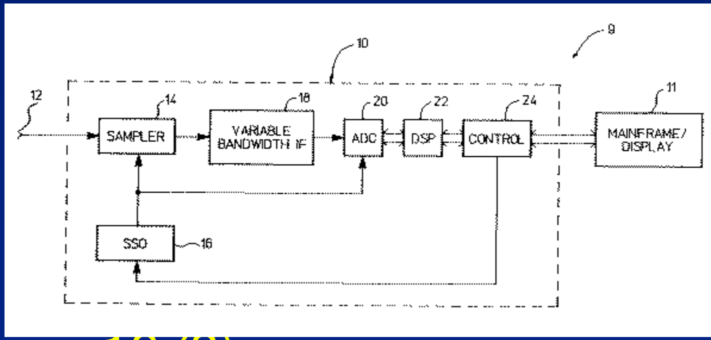
- Gated counter/interval timer (Agoston, Tektronix, 1986)
- Picosecond resolution (Dobos, Tektronix) (1988, 1994)
- Phase correction (Dobos, Tektronix, 2001)



# Oscillography: Time bases

## Problem: Missing waveforms

## Solution: Coherent time base

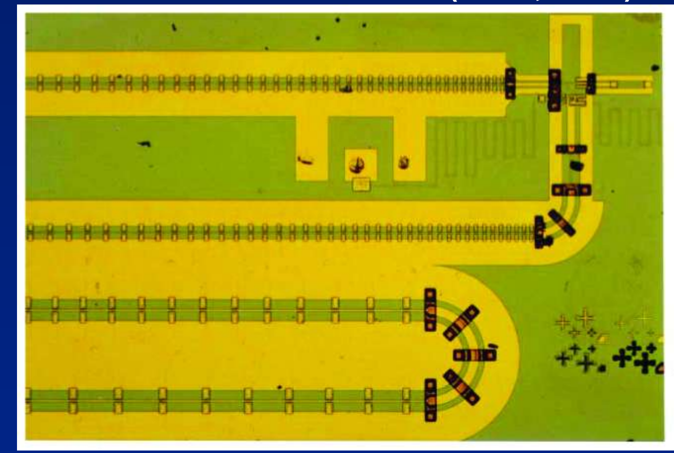



- Strobe predictor with random jitter (Andrews, 1973)
- PLL + VCO + DAC (Agoston, Tektronix, 1986)
- Microwave Transition Analyzer (MTA)(Marzalek, et al., 1991):

  FFT + sampling strobe synthesizer
- Coherent timebase (Reynolds, Slizynski, 1998)
- Triggered Time Interpolation (Kimura, et al., 2001)

# Oscillography: *Nonlinear Transmission Line*

(Case, 1992)

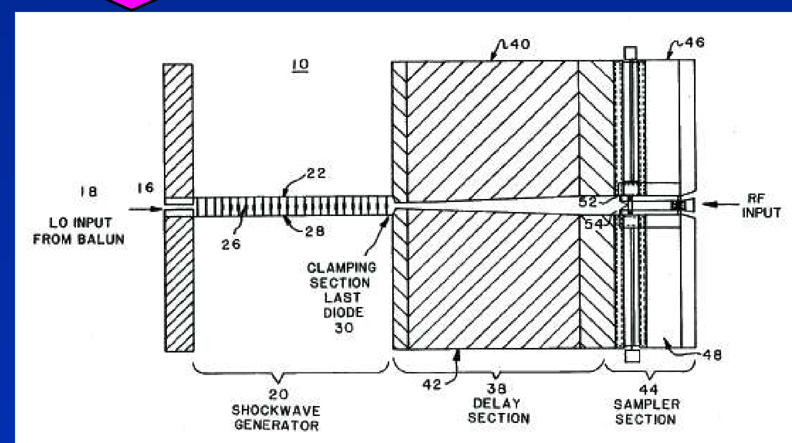


## Problem: SRD $t_r$ limited

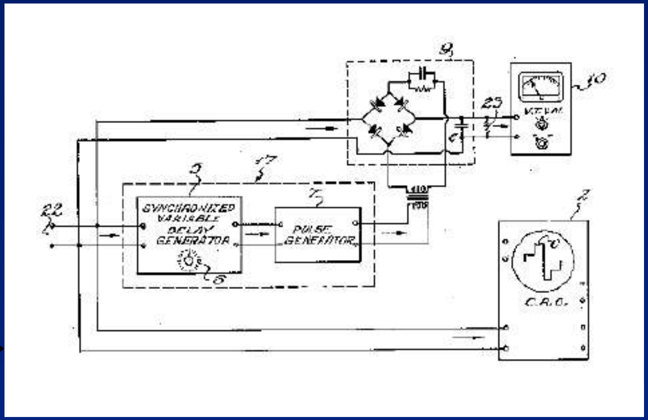
## Solution: Use NLTL

***NLTL combinations…***

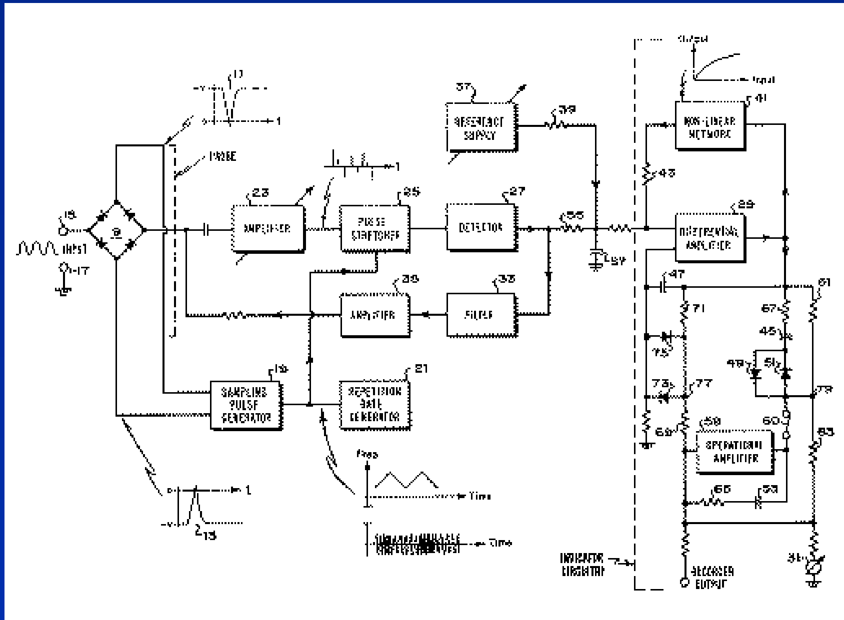
- NLTL + sampler: Rodwell (1988)
- NLTL + sampler + bridge: Marsland (1990)
- NLTL + sampler: Su, Tan, Anklam (HP, 1987-1990)
- NLTL + sampler for TDR: Yu, et al. (1991)
- Complete gate: SRD + sampler + NLTL: Whiteley, et al. (HP, 1991)
- Wafer probe: Shakouri (1993)
- 480 fs pulse: Van der Weide (1994)
- **PSPL sampling gate: Agoston, et al.**



# Sampling Voltmeters

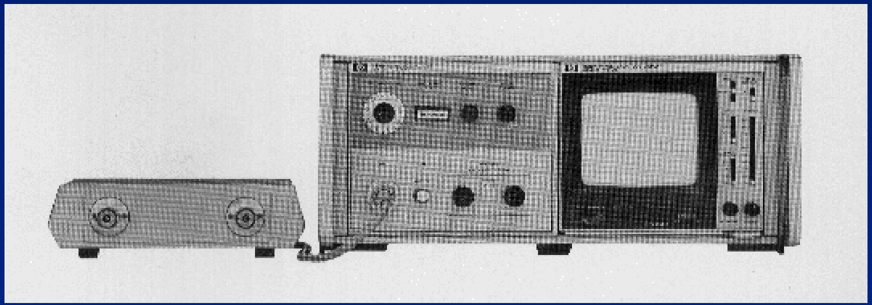



- Spencer (1949)
  - Gate connected to VTVM
- Hewlett-Packard (1960s)
  - HP 8405A [vector voltmeter] (Yen, 1964)
  - HP 3406A [scalar, incoherent] (Boatwright, 1964)
- McCracken (1969)
  - Phase point sampling voltmeter
- Mirri, et al. (1994)
  - Randomized vector voltmeter

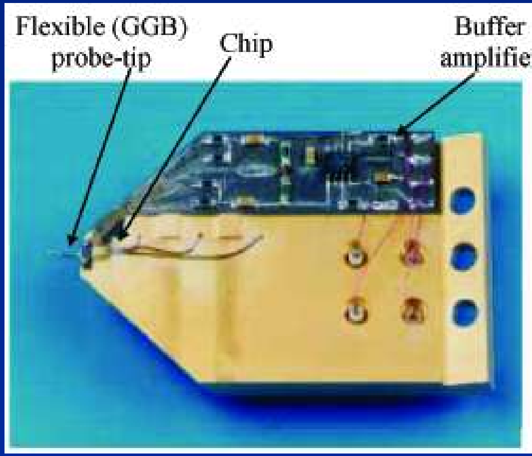


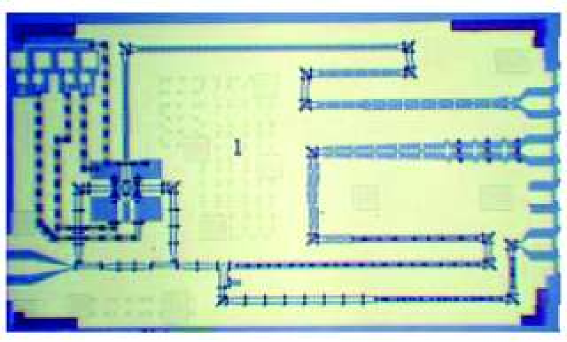
# Network Analyzers: *SRD driven Sampling gate*

***S parameter measurements***



- HP 8410A (1967)
  - Grove sampler
- HP 8510A (1984): Digital control
- Wiltron
  - False locking (Kapetanic, 1990)
  - Bias control distortion compensation (Grace, Kapetanic, Liu, 1990)
- Integrated VNA
  - Marsland (1990)
  - Wohlgemuth, et al. (1999)



# Network Analyzers: VNNA & LSNA

**Problem:** ***Measurement of nonlinear regions of operation***

**Solution:** ***Use non-ratioed (absolute) measurements***

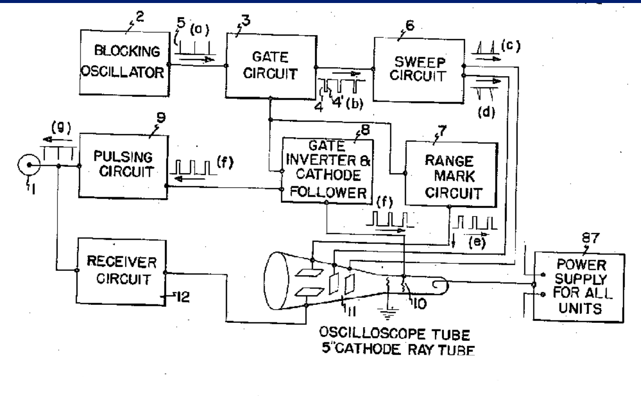
- *V*ector(ial) *N*onlinear *N*etwork *A*nalyzer
  - Sine Generator + Oscilloscope (7854):
    Sipilä, Lehtinen, Porra (1988)
  - Harmonic Generator + VNA: Lott (1989)
  - Oscilloscope + VNA: Kompa, van Raay (1990)
  - 4 channel Oscilloscope (54120T) + couplers:
    Van den Broeck, Verspecht (1992)
- *L*arge *S*ignal *N*etwork *A*nalyzer
  - Van Damme, et al. (2000)
  - Scott, et al. (2002)

# Microwave Counters

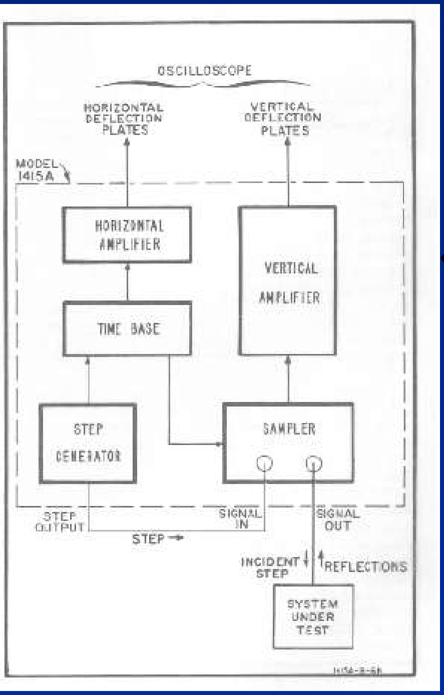
- *Techniques*
  - Prescaling (non-sampler)
  - Heterodyne (non-sampler)
  - Transfer Oscillator
    - Phase locks lower frequency oscillator to input
    - Single sampler (Chu, 1975)
  - Harmonic Heterodyne
    - Combines heterodyne with transfer oscillator method
    - Single sampler + microprocessor (Peregrino, Throne, 1977)
- *Gate improvements*
  - Thin film gate (Merkelo, 1971)
  - Thin film hybrid (Sayed, 1980)
  - GaAs gate (Gibson, 1986)

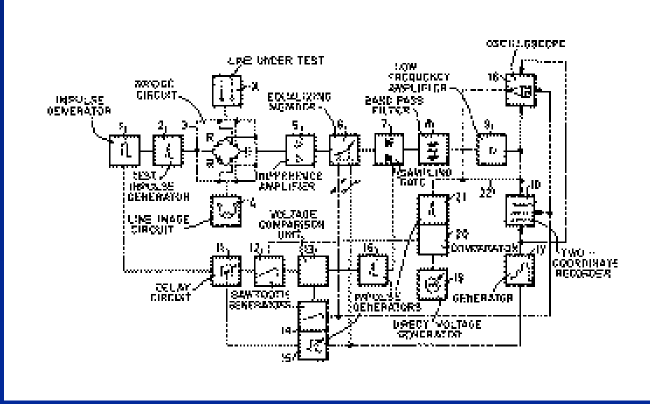
# Time Domain Reflectometry

- Non sampling
  - Dévot (1948)
  - Bauer (Siemens) (1962)




- Sampling
  - HP 1415A (1964)
    - 50 ps pulser
    - 188A gate
  - Frye (Tektronix) (1965)
  - Differential
    - McTigue & Duff (1996)
    - McEwan (1995)
  - 2.3 ps TDR (NLTL)
    - Yu, et al. (1991)



# Computer Assisted Measurements

- *Computer interfaces: digital signal processing*
  - CAOS (Stuckert, 1969)
  - NBS TDNA (Andrews, et al., 1969-1978)
- *Time base correction due to jitter and drift*
  - Deconvolution: Gans (1983)
  - Markov estimation: Souders, et al. (1990)
  - Phase demodulation: Verspecht (1994)
  - Distortion compensation: Schoukens, et al. (1997)
- *Deconvolution & Normalization of sampler*
  - Frequency Domain complications: Nahman and Riad (1974-1990)
  - Sampler Characterization
    - Riad's Grove sampler model (1978-1982)
    - Nose-to-nose (Rush, Verspecht, 1990-1995; **Scott**)
    - Analytic model (**Remley, Williams**)

# Future improvements

## (courtesy of M. Rodwell, UCSB)

- *Sampling Oscilloscopes*
  - Improved timebase stability and flexibility in triggering
  - Better time bases: PLL, DDS, …
  - Network-analyzer-like calibration procedures
- *Network Analysis*
  - combined accuracy, frequency coverage, and cost
  - better calibration methods needed for testing above 300 GHz $f_t$ and $f_{max}$

# Acknowledgements


- J.R. Andrews (PSPL)
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- Acoustics Lab, HUT
- Fulbright CIES

# Conclusion

The End