

TRANSMISSION CHANNEL CHARACTERIZATION BY IMPULSE RESPONSE MEASUREMENTS



OT

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R.F. LINFIELD
R.W. HUBBARD
L.E. PRATT



U.S. DEPARTMENT OF COMMERCE
Elliot L. Richardson, Secretary

Betsy Ancker-Johnson, Ph. D.
Assistant Secretary for Science and Technology

OFFICE OF TELECOMMUNICATIONS
John M. Richardson, Acting Director



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TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES	iv
LIST OF TABLES	v
ABSTRACT	1
1. INTRODUCTION	1
2. BASIC CONCEPTS	3
2.1 Time-Invariant Filters	3
2.2 Time-Variant Filters	5
2.3 Transmission Channel as Time-Variant Filters	8
3. DESIGN STRATEGIES	11
3.1 Gross Characteristics of the Channel	12
3.2 Signal Selection	16
3.3 Detection Schemes	20
3.4 Examples of System Configurations	22
4. SYSTEM IMPLEMENTATION	34
4.1 Background	34
4.2 The Present ITS System	38
4.3 Applications, Examples of Results and Future Plans	43
5. CONCLUDING REMARKS	50
REFERENCES	51

LIST OF FIGURES

	<u>Page</u>
Figure 1. Time variant filters response representations.	6
Figure 2. Simplified block diagram of measurement schemes.	9
Figure 3. Transmission channel as time variant filter.	10
Figure 4. Example of impulse response on air-ground link.	14
Figure 5. Example of signaling waveforms and their auto-correlation functions.	19
Figure 6. Synchronous detection schemes.	21
Figure 7. Block diagram of single pulse sequence system configuration.	23
Figure 8. Delay line matched filtering for pseudorandom rectangular waveforms.	24
Figure 9. Block diagram of matched filter system configuration.	26
Figure 10. Schematic of interdigital transducer design for biphase code surface wave devices.	27
Figure 11. Block diagram of multiplexed correlator system configuration.	28
Figure 12. Pseudorandom sequence generators.	30
Figure 13. Maximum length shift register sequence characteristics.	31
Figure 14. ITS system - transmit terminal.	40
Figure 15. ITS system - receiver front end.	41

	<u>Page</u>
Figure 16. ITS system - signal processor.	42
Figure 17. Impulse response between Haleakala and Kona, Hawaii, March 18, 1974 at 2 second intervals.	44
Figure 18. Mt. Venda to Aviano (Italy) path test data, September, 1975.	46
Figure 19. Concept for cross-correlation measurement.	48

LIST OF TABLES

Table 1. Gross channel parameters.	15
Table 2. Estimates of delays for specific channels.	17
Table 3. Summary of characteristics of some pulse sounding systems.	37

TRANSMISSION CHANNEL CHARACTERIZATION BY IMPULSE RESPONSE MEASUREMENTS

R.F. Linfield
R.W. Hubbard
L.E. Pratt*

Some basic concepts, design criteria and hardware implementations are reviewed for measuring the impulse responses which characterize radio transmission channels. A channel sounder which is presently being used by the Institute for Telecommunication Sciences (ITS) is described. The sounder was implemented for easy transport and operational convenience in collecting response data on a variety of transmission paths and over a wide frequency range. Some applications and measurement results are presented to illustrate the capabilities.

Key words: Channel characterization, impulse response, pseudo-random signals, microwave transmission, time-variant filters, correlation processing.

1. INTRODUCTION

The demand for electromagnetic spectrum space is continually increasing to meet the expanding need for telecommunication services. Advanced systems now use frequencies extending into the microwave and millimeter wave region and require bandwidths capable of transmitting hundreds of megabits per second. Because there is an ever increasing emphasis on the performance of such systems and because of the constant need for more efficient use of the spectrum, it is essential that the transmission channel be accurately modeled. Valid channel models are crucial in the design and evaluation of these systems because at the higher frequencies and bandwidths, the channel capacities are limited not only by additive noise, but by distortion caused by the propagation medium. For example, in many communication channels, the signal propagates to the

*The authors are with the Institute for Telecommunication Sciences, Office of Telecommunications, U.S. Department of Commerce, Boulder, Colorado 80302

receiver over several different paths, arriving with different amplitudes and delays. These multipath signals add vectorally in the receiver causing phase and amplitude distortion as a function of time and frequency. Combating the degrading effects of multipath requires knowledge of its structure. The prime purpose of the measurement techniques discussed here is to characterize this multipath structure.

Theoretically, if the response to an impulse function were known with sufficient accuracy, all magnitudes and rates of change of signals could be computed. Bullington (1970) notes that in practice this possibility is somewhat an illusion because many different impulse responses occur on any given path, with significant diurnal and seasonal changes. The concern here is with channel variations occurring on the order of seconds whose effect on system performance depends on signal design parameters such as modulation or coding and on receiver system design. Variations which are short compared to say a pulse length in digital transmission are of interest only in some averaged form. Those which occur diurnally or seasonally cannot be alleviated by system design except by providing sufficient performance margin by increasing signalling power [Schwartz, et al., 1966].

Generally, the communication channel varies with time as meteorological conditions change. A time-varying channel can be represented as a time-varying filter with additive noise at the output. Such filters can be characterized by a frequency response function or its Fourier transform, the impulse response function. Given either of these functions, it is possible to find the response of the filter (or channel) to any arbitrary input signal. In this report, the emphasis is on impulse response functions not only because they completely specify the state of the channel as a transmission link, but also because they are easy to measure and they permit one to observe multipath components directly and to relate multipath structure to meteorological parameters. Computer analysis can be used to reduce collection of impulse response data to a few functions to describe appropriately the channel characteristics [Hubbard, 1971].

Techniques for measuring the time-variant impulse response of a transmission channel are developed in this paper. Different types of systems which have been used for this purpose are reviewed and a system presently being used by ITS is described. Applications, examples of data collected, and future plans are discussed.

2. BASIC CONCEPTS

The fundamental relationships concerning the transmission of arbitrary signals through linear electrical networks are presented first. Emphasis is on the time response functions rather than frequency response functions, since either can be derived from the other. Correlation and matched filter techniques for measuring the impulse response using either a unit impulse or white noise are discussed for the time-invariant filter case. These techniques are then extended to the time-variant filter under certain constraints. A radio transmission channel is shown to be representable by a certain type of linear time-variant filter. The same measurement process is then applied to the channel, but with additional constraints imposed by bandwidth limitations and terminal separation.

2.1 Time-Invariant Filters

A linear time-invariant filter can be characterized in two different, but related ways: the complex transfer function in the frequency domain or the impulse function in the time domain. Given either of these functions, the filter output can be determined for any arbitrary input signal. There is a wealth of mathematically oriented literature on the concepts considered below. A good general reference is Gallager (1964).

The impulse response $h(t)$ of a filter is defined as the output of the filter when a unit impulse $\delta(t)$ is impressed on the input. The complex transfer function is a direct Fourier transform of $h(t)$:

$$H(f) = \int_{-\infty}^{\infty} h(t) e^{-j2\pi ft} dt \quad (1)$$

Given $h(t)$ an arbitrary input $x(t)$ produces an output $y(t)$ which is given by the convolution integral

$$y(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau) d\tau = x(t) * h(t) \quad (2)$$

where $*$ denotes convolution. The convolution of a function $f(t)$ with the unit impulse function $\delta(t)$ yields the function itself:

$$f(t) * \delta(t) = f(t). \quad (3)$$

An obvious way to measure the impulse response of a network is to transmit a unit impulse and observe the output response. However, in practice it is only possible to approximate a unit impulse. The width of the pulse actually used must be much less than the response time of the filter to be measured or at least less than the reciprocal of the bandwidth of any signal to be passed through the filter.

An alternative is to use impulse type functions. If the input to the filter $x(t)$ has an autocorrelation function given by

$$R_{XX}(\tau) = 1/T \int_0^T x(t) x(t+\tau) dt, \quad (4)$$

then the cross-correlation of the output with the input is

$$R_{XY}(\tau) = 1/T \int_0^T y(t) x(t+\tau) dt \quad (5)$$

Substituting (2) into (5) and utilizing (4) yields:

$$R_{XY}(\tau) = \int_{-\infty}^{\infty} h(t-\tau)R_{XX}(t) dt = h(\tau) * R_{XX}(\tau). \quad (6)$$

The cross-correlation $R_{XY}(\tau)$ yields the impulse response $h(t)$ when the input to the filter is a white noise source. That is, since

$$R_{XX}(\tau) = \delta(\tau) \quad (7)$$

for white noise, then (6) becomes

$$R_{xy}(\tau) = h(t) * \delta(t) = h(\tau). \quad (8)$$

A non-white noise source can be used if the bandwidth of this source is much greater than the bandwidth of the filter. The cross-correlation technique for measuring the impulse responses requires that replica of the input signals be available at the output. It is possible, as will be shown later, that this requirement can be eliminated even for noise sources if a matched filter is used for detecting the response.

2.2 Time-Variant Filters

A more general form of the convolution integral applies when the filter parameters vary with time [Kailath, 1962] as

$$y(t) = \int_{-\infty}^{\infty} x(\tau) h(t, \tau) d\tau, \quad (9)$$

where $h(t, \tau)$ is a function of two variables, t and τ , other than the form $t-\tau$ used before.

The time-variant filter response can be measured under certain constraints as shown by Kailath (1962). A sample baseband response of a time-variant filter is shown in figure 1. Input pulses occurring periodically at intervals ΔT are depicted along the time axis t . Successive responses $h(t_n, \tau)$ at t_0, t_1 , and t_2 are shown plotted along the delay axis, τ , each differing somewhat from the previous response. Any one of these responses can be characterized by n samples taken at intervals of $\Delta\tau = 1/(2B)$ where B is the maximum bandwidth of the response as a function of delay. If the response is zero outside an interval, L , then $n=L/(\Delta\tau)$ samples are required to characterize each response. The successive responses $h(t_n, \tau)$ may be considered as slices taken through the time axis at intervals ΔT . A large number of slices over long periods of time are required to represent the time-variant response.

It is apparent that n slices taken at intervals $\Delta\tau$ along the τ axis can also be used to characterize the response. One such slice is shown in figure 1 and denoted at $h(t, \tau_n)$. These slices can also be represented by samples taken at

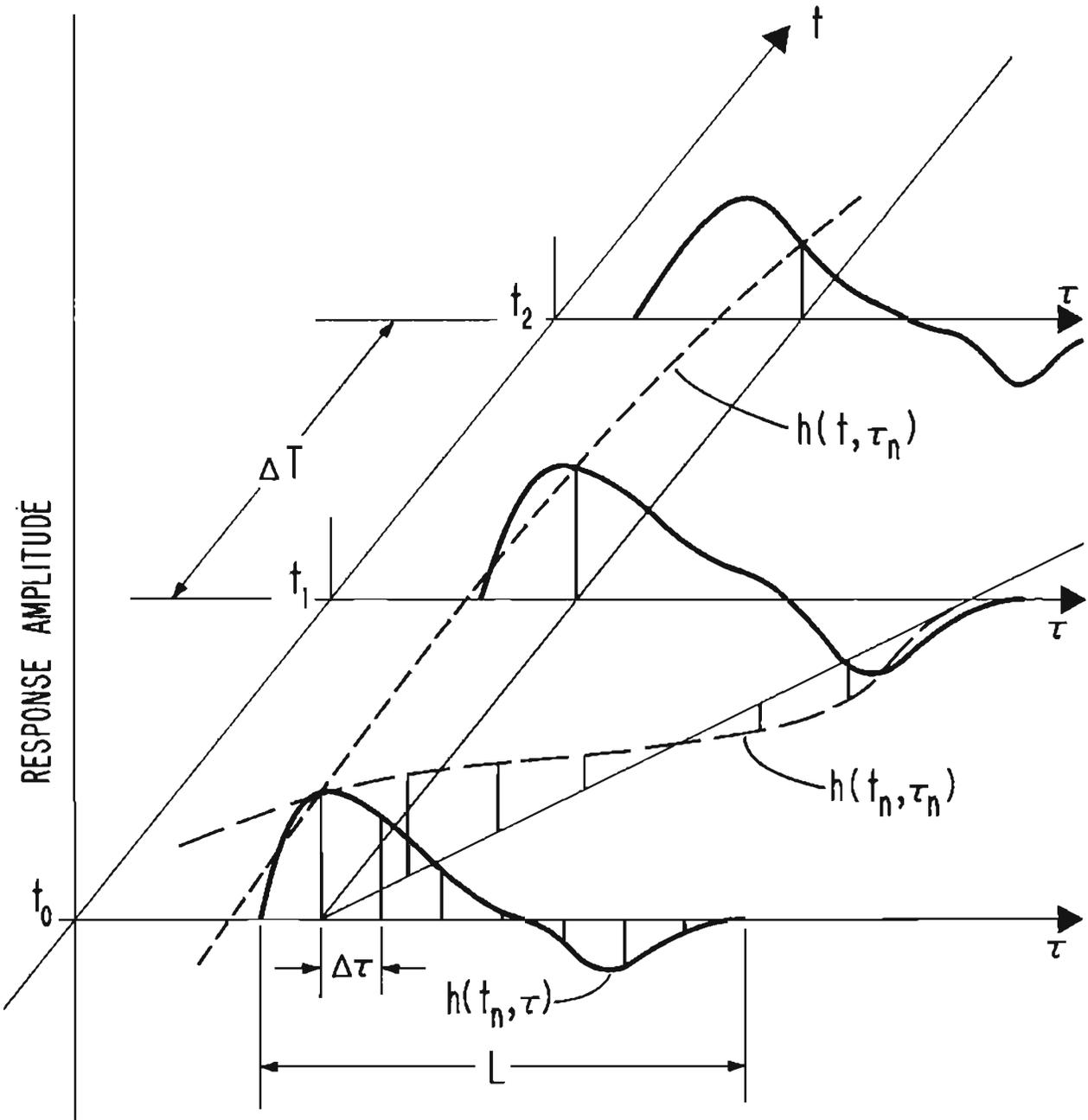


Figure 1. Time variant filters response representations.

intervals of ΔT and used to reconstruct the response $h(t, \tau_n)$ by the sampling theorem to represent a waveform of bandwidth $W = 1/(2\Delta T)$. Note that n such waveforms are required to characterize the response as long as the time variations occupy a bandwidth which is less than or equal to W . The basic criterion is that

$$n\Delta\tau = L \text{ where } L \leq \Delta T \leq 1/2W. \quad (10)$$

The method used to measure the time-variant impulse response has important implications on the bandwidths required to record data. Measurement techniques which involve taking slices through the time axis require bandwidths of at least B where as recording n slices through the delay axis requires a bandwidth of $nW = 2IWB$. If $LW \ll 1/2$ then the recording bandwidth can be reduced by a substantial amount.

When $\Delta T \ll 1/2W$ and $L \leq \Delta T$, it is possible to characterize the response by taking a sample at each increment of time and delay as shown in figure 1 for $h(t_n, \tau_n)$. The impulse response waveform can be reproduced by passing these samples through a filter with bandwidth given by:

$$1/(2\Delta T) = 1/(2n\Delta\tau). \quad (11)$$

This waveform is just one diagonal slice through the time-variant response with the delay time scale stretched by a factor n .

In summary, the time-variant filter impulse response can be reproduced under certain constraints from three different types of measurement. Each measurement scheme involves a different implementation as indicated in the following table:

<u>Representation</u>	<u>Measurement Scheme</u>
Delay slices through the time axis, $h(t_n, \tau)$	Matched Filter
Time slices through the delay axis $h(t, \tau_n)$	Multiple correlators
Diagonal slices through the time & delay axis $h(t_n, \tau_n)$	Single time multiplexed correlator

Simplified block diagrams for these three measurement schemes operating at baseband are shown in figure 2. Implementation schemes for modulating carriers and bandpass sampling are given in Section 3.

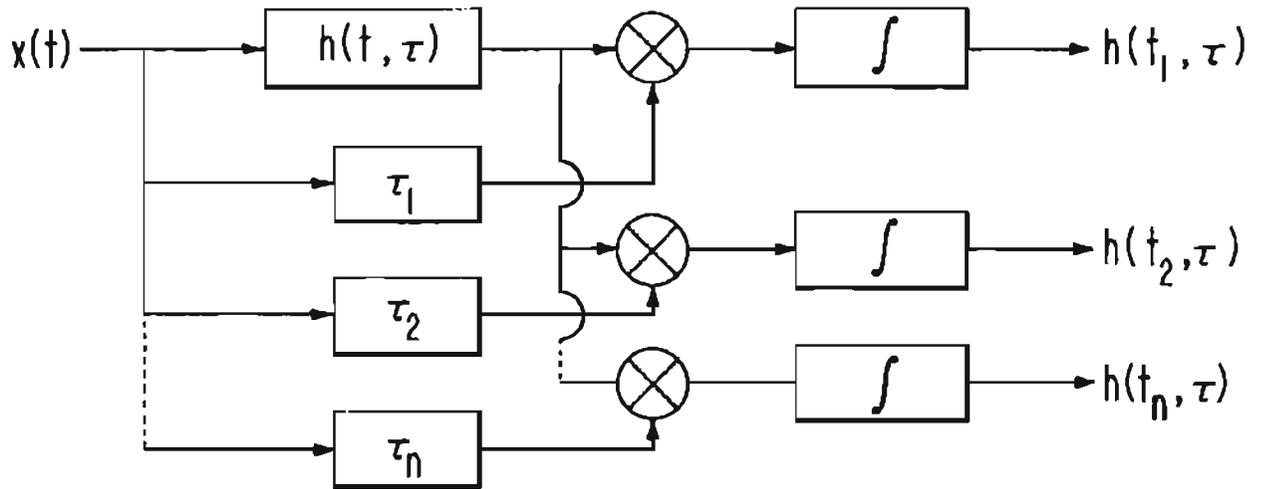
2.3 Transmission Channel as Time-Variant Filters

It is assumed here that the radio transmission channel can be considered as a link in a system with input and output terminals corresponding to the antenna terminals at the transmitter and receiver as shown in figure 3. Actually, communication system performance is affected by all portions of the system which distort the signal (by bandlimiting and nonlinearities in the transmitter, for example) or which add noise to the signal (front end thermal noise in the receiver for example). These equipment characteristics are not considered here because they depend upon the type of modulation used for communicating. The affects of filtering by a specific transmitter and receiver can be measured independently. Transmission channel impulse response measurements then assume that any distortion caused by the transmitter or the receiver be included in the definition of the effective input signal.

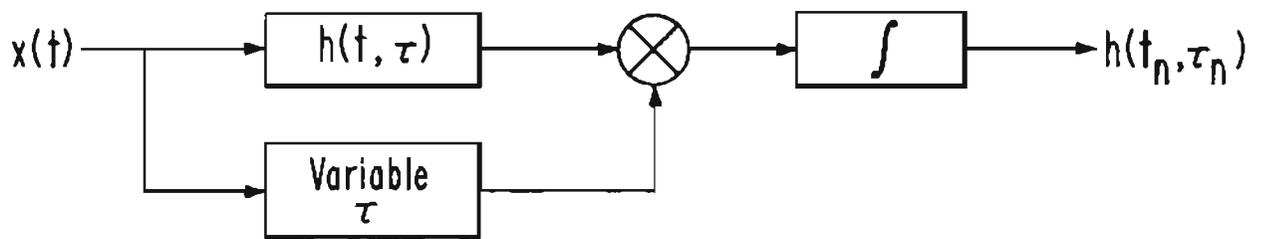
The transmission channel, as a section of a system, has characteristics similar to a two terminal network. Input signals are delivered to the output via various paths (figure 3a) having different delays and attenuations which may vary with time. Output power is determined by the vector sum of these input signals arriving via the various paths and may include some noise power even when no signal is applied to the input. A block diagram of the transmission channel is shown in figure 3b.



(a) MATCHED FILTER TECHNIQUE.



(b) MULTIPLE CORRELATORS



(c) TIME MULTIPLEXED CORRELATOR

Figure 2. Simplified block diagram of measurement schemes.

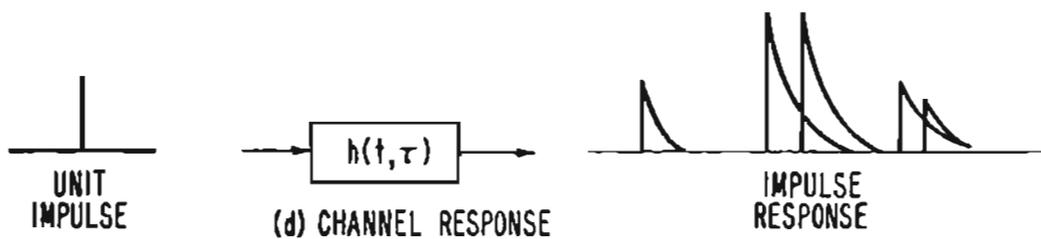
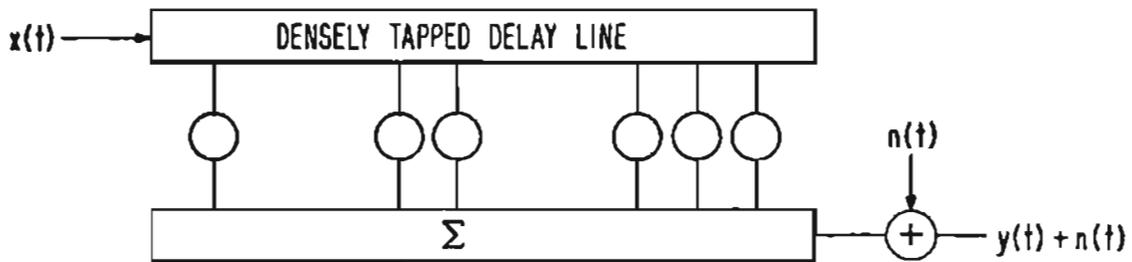
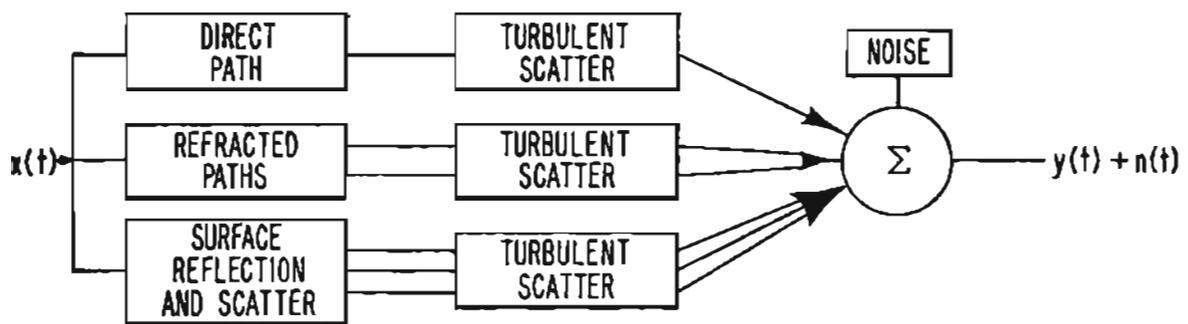
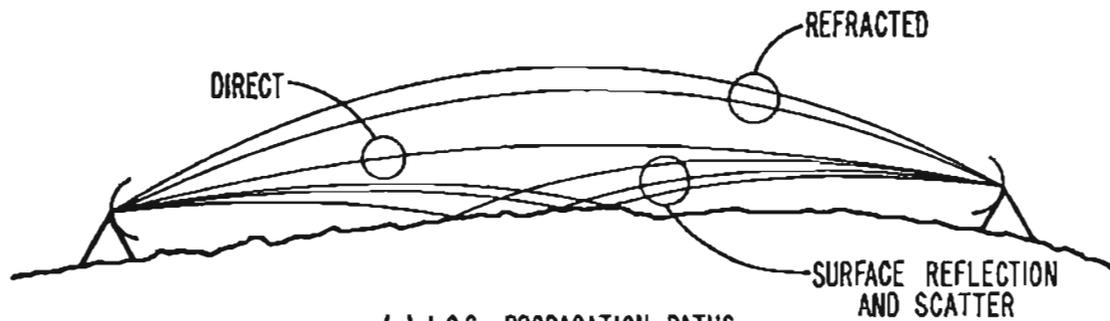


Figure 3. Transmission channel as time variant filter.

This system link can be represented by a non-recursive transversal filter consisting of a densely tapped delay line as shown in figure 3c. See, for example, Kailath (1962). Relative delays correspond to relative path delays and the relative tap gains correspond to path attenuations. Since the channel characteristics may vary with time, the tap delays and gains may also vary with time.

The impulse response at a given instant in time may appear as indicated in figure 3d, assuming the peak amplitudes of the received pulses are large compared to the noise. This single response displays the multipath structure at a given instant, but yields no insight into the time variations. These require many such measurements over long periods of time.

Impulse response measurements on the transmission channel introduce new restrictions to the measurement process. These include:

- a) peak power limitations on the transmitter which preclude a true impulse
- b) additive noise and interference in the channel which contaminate the measurements
- c) large separation of input and output terminals
- d) non-stationary time-varying processes which require extended measurement points
- e) interference to other users of the channel which restrict channel usage.

Methods for overcoming or circumventing most of these added restrictions are discussed in the following section.

3. DESIGN STRATEGIES

The selection of a channel probing signal, detection schemes, and data collection techniques requires some prior knowledge of the response time of the channel, the expected noise level, and the bandwidth of interest. Gross estimates can be made for many channels. Here, the emphasis is on channels utilizing centimeter and millimeter wavelengths.

Gross characteristics are given in the following subsection for line-of-sight (LOS) links including terrestrial, airborne and satellite terminals. Subsequent subsections discuss signal selection, noise, and signal detection. Simplified block diagrams of some complete system configurations are also presented.

3.1 Gross Characteristics of the Channel

Estimates of the multipath delay spread, L , the Doppler spread, W , and the bandwidth, B , can be made for various types of links, operating frequencies, terminal locations, separations, and velocities. The choice of the right approximation to the input impulse and its repetition period for measuring the channel response function depends on these gross estimates.

Links may be categorized on the basis of terminal location, e.g., ground-ground, ground-air, ground-space, air-air, air-space, or combinations of these, such as ground-air via space relay.

Ideally, each link would involve only one signal propagation path, but unfortunately several signal paths exist and are received simultaneously. Even under the ideal condition of a single path in a homogeneous gaseous atmosphere, the propagating medium is dispersive above 10 GHz due to the frequency dependence of the complex dielectric constant of water vapor and oxygen. Ionospheric scintillations and atmospheric turbulence cause additional delay spreading due to volume scattering. When the earth's surface is within view of the main lobes of the transmitting and receiving antenna, signal components may be reflected or scattered from the terrain into the receiver. Additional paths sometimes exist at certain ranges with low antenna elevation angles due to atmospheric refraction. Index of refraction gradients can also cause "radio holes" and power fades depending on defocusing and earth diffraction effects. Precipitation, particularly rain, causes deep fades at higher frequencies. A survey of the fading mechanisms is given by Dougherty (1968) and the effect of hydrometers by Samson and Kirby (1973), and by Craft (1971).

The magnitude, phase and polarization of all of the signal components are continually varying relative to each other as meteorological conditions change. When one or both terminals are in motion, the propagating mechanism becomes even more complicated by the introduction of doppler shifts and refracted, reflected, and scattered signals may come and go as the character of each continually changes.

A possible impulse response indicating some typical values for dispersion, turbulent scatter, surface reflection, surface scatter and atmospheric refraction is shown in figure 4. This example grossly approximates the response that might be observed on an air-ground link under certain weather conditions at one instant in time. The airborne terminal is assumed to be at a height of 10 km, a range of 200 km and an elevation angle of 3° . An atmospheric layer with a negative refractive index gradient may cause additional refracted paths to exist at this low elevation angle. As the airborne terminal moves toward the ground terminal (decreasing range), the refracted path delays decrease. These signal components ultimately fade as the elevation angle increases. At the same time, the delays of the surface reflected components increase and their amplitudes decrease. The delay spread due to scattering increases as the elevation angle increases. Ultimately, the surface reflected components disappear due to discrimination by the antenna pattern.

The dispersive properties of the atmospheric absorption are usually masked by atmospheric multipath. Both dispersion and scattering occur on all multipath components.

In order to resolve dispersive effects and to distinguish between signal components delayed by an infinitesimal amount, an impulse measurement system would require a signaling waveform and receiver with extremely large bandwidth which may be impractical. However, response data of interest to the communicator are only those observable within an individual message interval whose effect on communications system performance depends on the choice of modulation and receiver design. Therefore, the

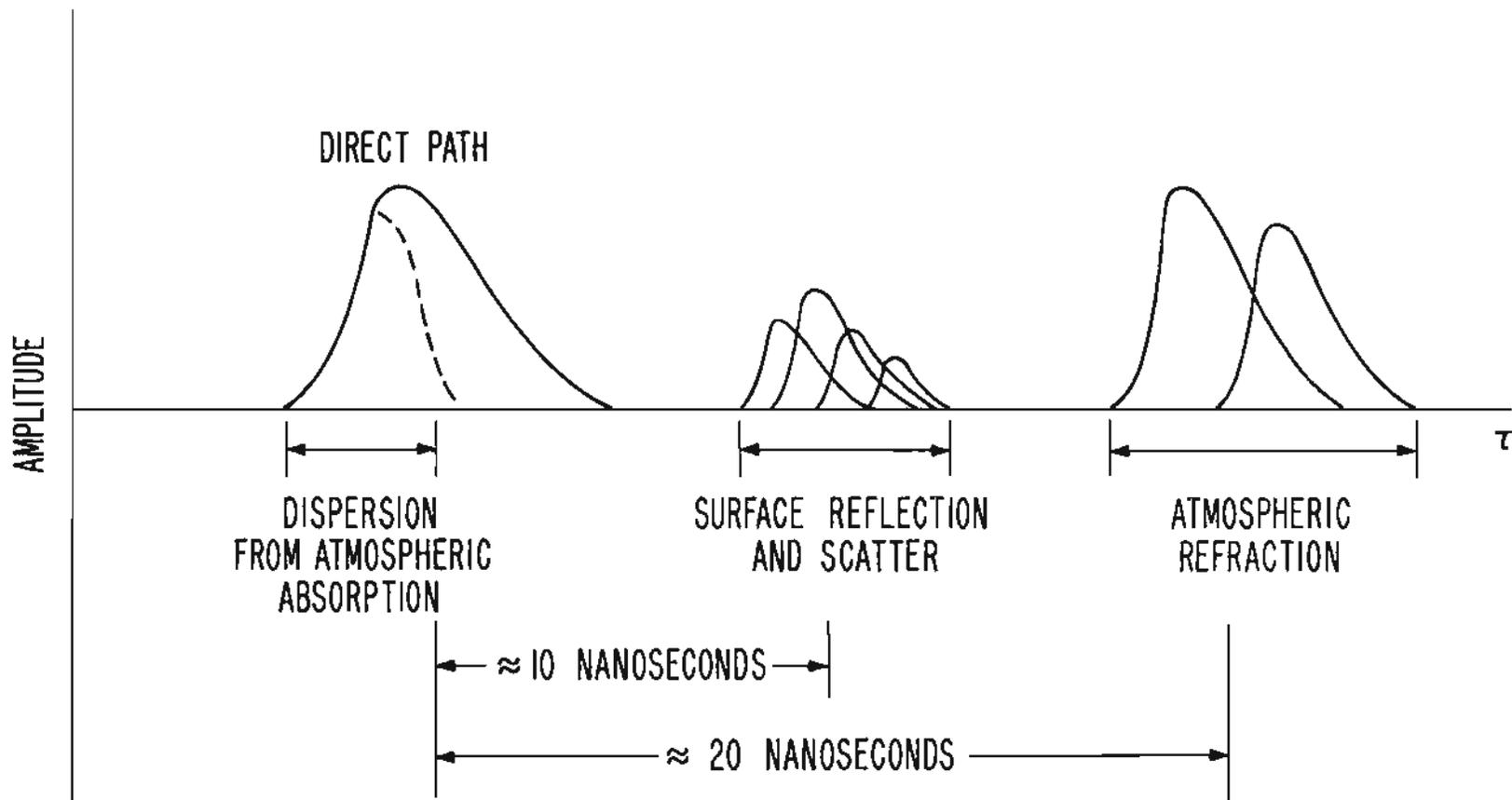


Figure 4. Example of impulse response on air-ground link.

bandwidth of the measuring system is related to the maximum data rate which may be applied to the channel.

Variations in the channel response with time which determine the periodicity of the measurement signal may occur slowly--seconds, minutes or even hours and days.

It is convenient to classify these changes into long-term and short-term variations. Long-term variations are caused by slowly varying changes in the propagation medium and short-term variations are attributed to phase interference among simultaneously occurring modes of propagation. Norton, et.al., (1955) define short-term as that maximum length of time within which fading is primarily due to phase interference and a negligible component of the variance in transmission loss is due to other causes. The actual times may vary from less than a minute to several hours depending on frequency. Barsis, et. al., (1962) classify "short-term" as variability within a single hour and "long-term" as variability of the hourly medians. This time variability can only be alleviated by providing adequate performance margin in the communications system design. Performance margin insures reliability, determines time availability, and depends on transmitter power, antenna gain and path attenuation as well as signal design.

It is possible to indicate orders of magnitude for delay spread and time variability for different types of channels. Estimates are tabulated below for links operating in the 1 to 100 GHz band. They were derived from data in an unpublished ITS memorandum report by Linfield*.

Table 1. Gross Channel Parameters

Channel	Delay Spread	Variability Time Scale
a) Atmospheric Dispersion	<0.1 ns	days-months
b) Volume Scattering	<1.0 ns	seconds
c) Ionospheric Scintillation	<1.0 ns	seconds
d) Tropospheric Refraction	<100 ns	minutes
e) Terrain Reflection		hours
Ground-Air	10 ns	
Air-Space	10 μ s	
f) Terrain Scatter	10-100 ns	hours

*R.F. Linfield (1975) Simulation of Avionics Line of Sight Radio Transmission Channel, Technical Memorandum 75-204. OT/ITS, Boulder, Colorado.

Item a) is negligible below approximately 15 GHz. Items a) and b) can exist on all links which include a terrestrial terminal and item c) on any link which includes a space terminal. Item d) occurs only under certain weather conditions and at antenna elevation angles less than about 5°. Items d) and e) are delays relative to the direct path. Items e) and f) may occur when the ground is illuminated by both terminal antennas and when mountains or buildings are near the path. Item f) may occur at higher grazing angles over rough terrain. The relative delay for item e) depends on terminal antenna heights and separations.

More detailed estimates of path delays and the effects of terminal motion are indicated in table 2. These estimates are for an air-ground link and an air-space link. It is assumed that the ground terminal antenna is 30 meters above the surface. The air terminal is an aircraft flying a 3 km circular orbit at 250 m/s at ranges and altitudes yielding the indicated elevation angles. The space terminal is a satellite in synchronous orbit.

3.2 Signal Selection

Impulse measuring equipment would typically require detected signal to noise ratios to exceed 10 dB. Given the expected noise levels, it is possible to select signals, transmitter power levels and antenna gains to achieve the desired ratio. Signal selection processes are considered below.

There are several conflicting requirements for selecting signals to use in channel response measurements. They include:

- a) Signals should be wideband in order to distinguish between received components arriving by different time delays. However, spectral components outside the bandwidth needed should be small to prevent interference to users of nearby channels.

Table 2. Estimates of delays for specific channels.

Elevation Angle	Air-Ground			Air-Satellite		
	<3°	10°	45°	<3°	10°	45°
<u>Multipath</u>						
Volume scatter	<1 nsec	<1 nsec	<1 nsec	<1 nsec	<1 nsec	<1 nsec
Ground reflection	5 nsec	20 nsec	100 nsec	2 μsec	12 μsec	50 μsec
17 Refracted components	100 nsec	--	--	100 nsec	--	--
Maximum rate	25 nsec			25 nsec		
<u>Terminal Motion</u>						
Max excursion (3 km orbit)	10 μsec	10 μsec	7 μsec	10 μsec	10 μsec	7 μsec
Max rate (250 m/s)	.83 μsec	.83 μsec	.56 μsec	.83 μsec	.83 μsec	.56 μsec

- b) The pulse repetition rate should be at least as long as the multipath duration. At the same time, it must be sufficiently short in order to measure adequately the time variability.
- c) Signal amplitude should be large to overcome the additive noise introduced by the channel and receiver. Peak signal power, however, should not exceed the linear range of terminal equipment (the transmitter's peak power limitation for example).

In addition, the signal selection process should consider the practicability of signal generation including hardware costs and complexity, operational convenience, portability, reliability and recording techniques. The data analysis procedure can also impact on the design concept employed.

Examples of signals and their autocorrelation functions which are useful as probing signals are shown in figure 5 [see Huffman (1961) and Golomb (1964)]. Only single code groups are depicted, but these can be generated in a repeatable manner for probing time variant channels. Also, except for the Barker code sequence, the code length can be increased. The peak amplitudes shown in figure 5 are not relative but would be proportional to the code length used.

The single pulse is easy to generate, but has limited application in a high interference environment unless high peak power is used at the transmitter.

Pseudorandom codes (figure 5 b through d) can be used if their autocorrelation functions are sufficiently narrow to achieve the desired resolution. The code word length determines the system sensitivity and the element length or clocking rate determines the resolution.

The Barker sequence shown in figure 5 b is the longest known sequence and it therefore has limited application where high sensitivity is desired.

The shift register sequence of figure 5 c can be generated for various lengths with relatively simple logic circuitry.

Impulse equivalent pulse sequences described by Huffman (1961) and shown in figure 5 d may be of any arbitrary length. The autocorrelation function is exactly zero except at the peak and at one side lobe. In the example shown, the amplitudes of the component pulses have been chosen from a continuum of values. It is also possible to select the phase from a distinct set of phases and to generate polyphase codes with good autocorrelation properties as shown by Frank (1963). The use of impulse equivalent or polyphase sequences has not been widespread because of the increased complexity of terminal equipment.

3.3 Detection Schemes

There are two techniques for the optimum detection of signals in the presence of Gaussian noise: matched filtering and correlation. Although each detector involves a different arrangement, both give equivalent performance and both are considered synchronous or coherent detectors.

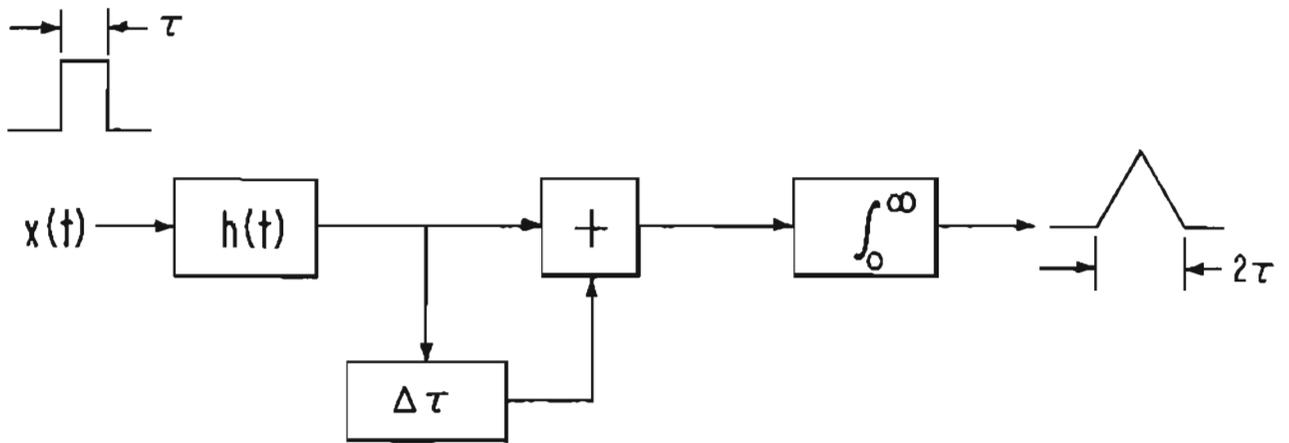
A matched filter is a linear filter whose impulse response $h(t)$ is a time-reversed replicum of the signal to be detected, i.e.,

$$h(t) = x(-t). \quad (12)$$

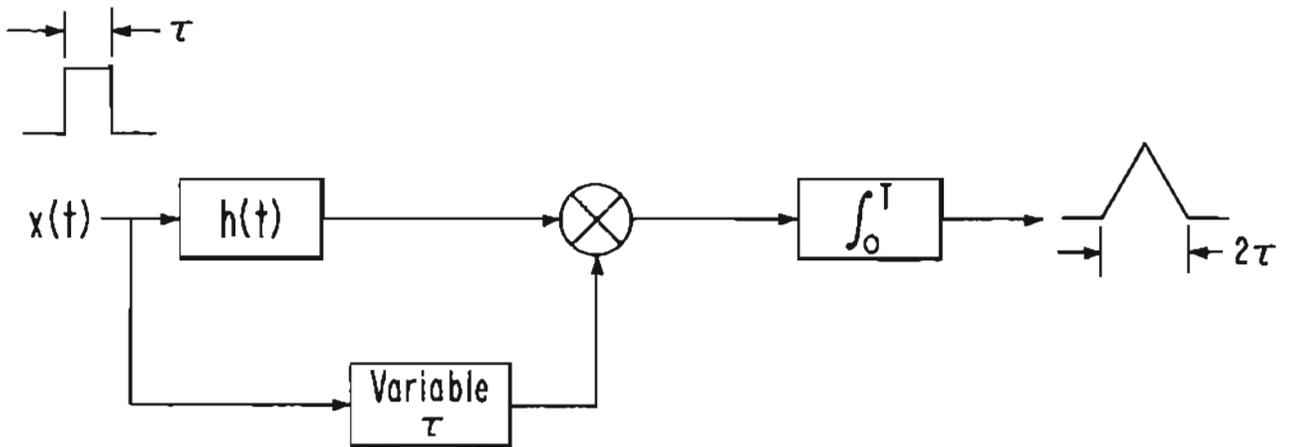
The output of such a filter is obtained by convolution

$$\begin{aligned} y(t) &= \int_{-\infty}^{\infty} x(\tau) h(t-\tau) d\tau = \int_{-\infty}^{\infty} x(\tau) x(\tau-t) d\tau \\ &= R_{xx}(\tau). \end{aligned} \quad (13)$$

The matched filter is therefore by definition a filter whose output signal is the autocorrelation function of the input signal. With a matched filter, it is not necessary to know in advance when the signal occurs since the filter computes the required integral continuously (see figure 6a).



(a) MATCHED FILTER FOR SINGLE RECTANGULAR PULSE



(b) CORRELATION TECHNIQUE

Figure 6. Synchronous detection schemes.

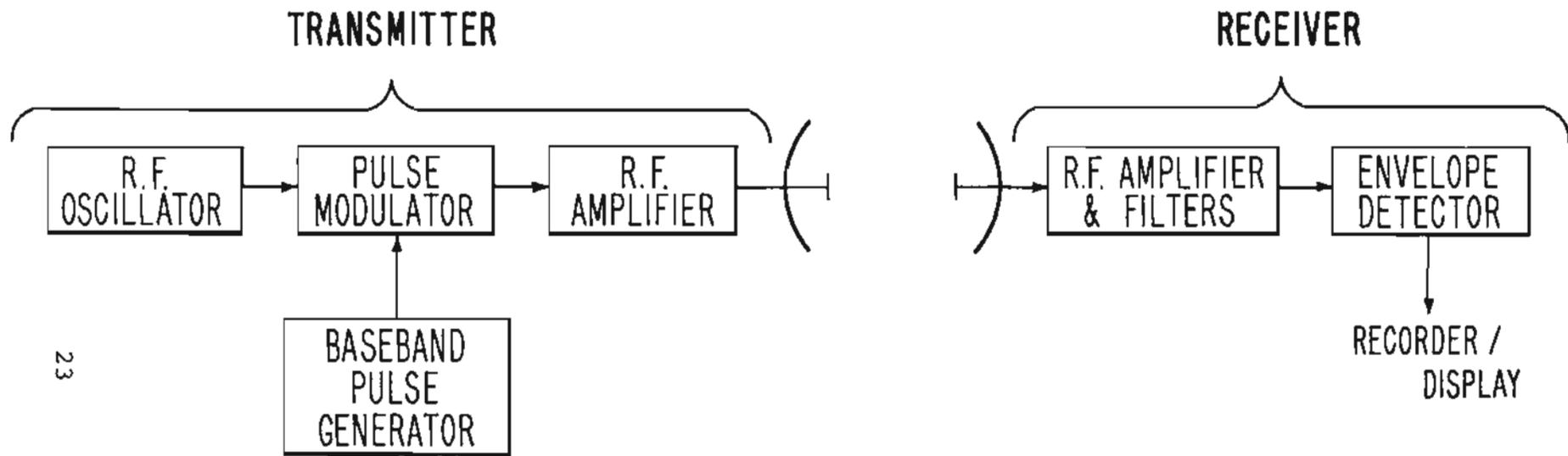
The correlator, however, does require a means of generating signals at the receiver and a precise knowledge of the timing of the signaling waveform. The correlator multiplies the input, consisting of signal plus noise, by a locally generated delayed replica of the input (14), and integrates this product as shown in figure 6b. The output of the correlator is, therefore, given by

$$y(\tau) = \int_0^T x(t)x(t-\tau) dt = R_{xx}(\tau). \quad (14)$$

3.4 Examples of System Configurations

As indicated previously, the most direct method for measuring the time varying impulse response of a channel is to transmit a short pulse of rf energy through it and observe the received pulses. A simple block diagram of such a system is shown in figure 7. This repetitive short pulse method has been used for some channel measurements. However, the system has two disadvantages noted earlier: 1) limited sensitivity due to peak power limitations of the transmitter, and 2) excessive bandwidth requirements for the data collection process. Although oscilloscope photographs can be used, it is more practical to sample the detected baseband and record $h(t, \tau_n)$ in a narrower bandwidth to overcome item 2. This adds complexity and cost to the system.

The transmitter peak power limitation can be circumvented by using pseudorandom rectangular waveforms as the signal source. One method of generating and detecting such waveforms is by using the tapped delay line matched filter configuration as shown in figure 8 for a baseband configuration. The generating filter consists of n delayed taps spaced at intervals, $\Delta\tau$, corresponding to the width of a single input pulse with a recurrence interval of ΔT . Each tap is connected to a common bus through a switch set for plus or minus one, according to the sequence desired. The output bus sums the tap outputs to provide a rectangular waveform of length $n\Delta\tau = \Delta T$. The receiving filter is a conjugate device identical to the generating filter except the switches are connected in reverse order. The receiving filter is followed by a continuous filter with a time

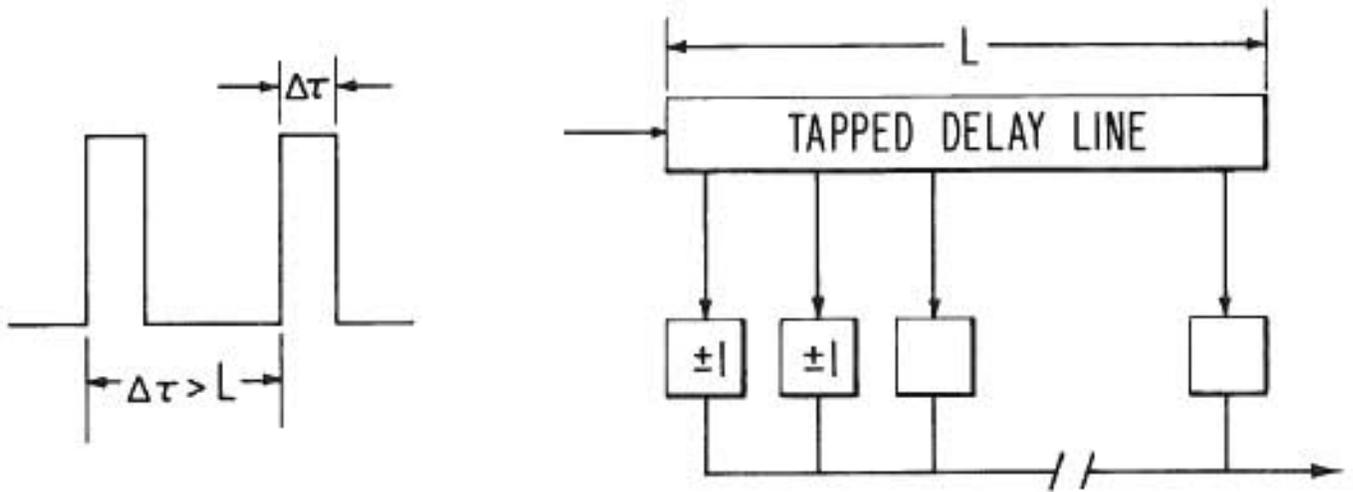


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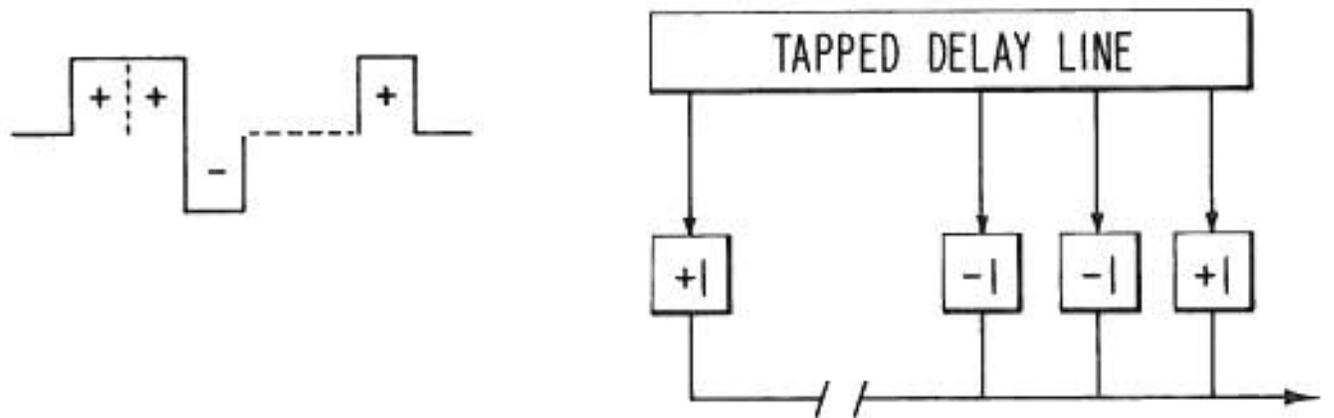
Figure 7. Block diagram of single pulse sequence system configuration.







(a) GENERATION



(b) DETECTION

Figure 8. Delay line matched filtering for pseudorandom rectangular waveforms.

constant, Δr . When $n\Delta r$ elements fill the line, the output is the autocorrelation of the input, i.e., a triangular pulse with baselength $2\Delta r$.

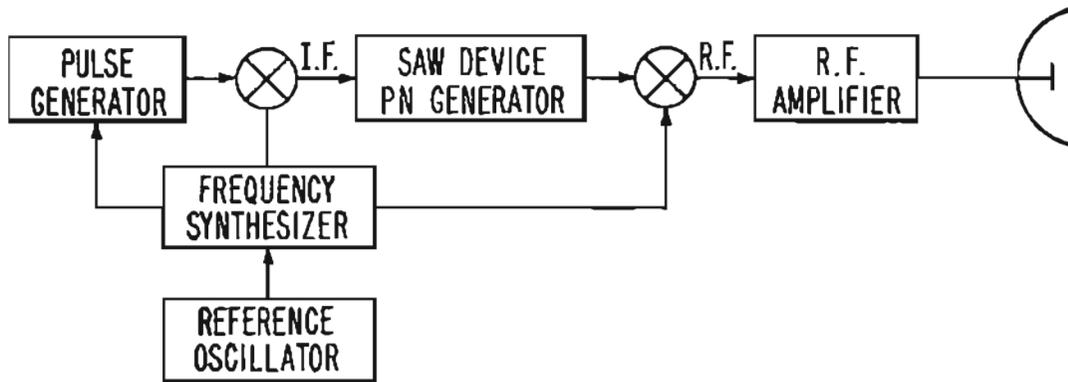
A measurement system utilizing this matched filter concept is shown in block diagram form in figure 9. In this configuration, an intermediate frequency (IF) is phase modulated by the pseudorandom sequence and then mixed to the rf carrier frequency for transmission.

At the receiver, the modulated carrier is reconverted to IF and decomposed into in-phase and quadrature components whose amplitudes are proportional to the sine and cosine of the modulation angle.

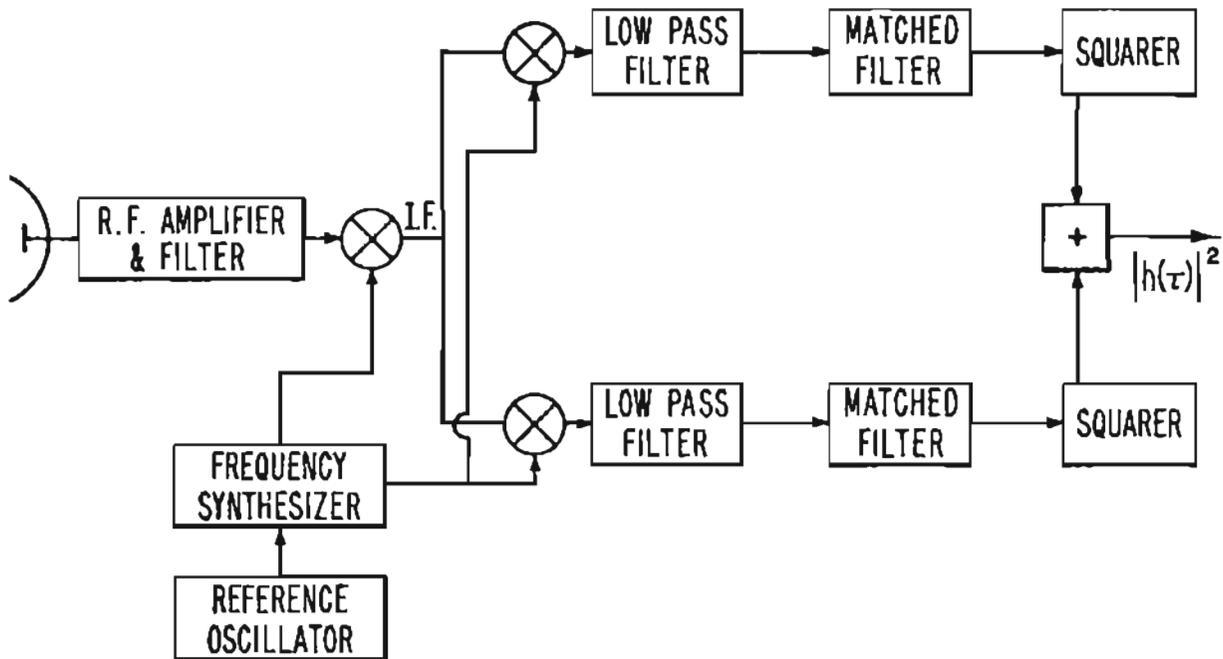
This matched filter system may be difficult to implement if the bandwidth is too wide or the code is very long. In some applications, pseudorandom sequences, phase shift keyed at IF, can be generated and detected using surface acoustic wave (SAW) devices. A schematic representation of a SAW device is shown in figure 10. A rectangular pulse at the input transducer causes an acoustic wave to propagate along the surface of the substrate under the taps. Each tap pair is spaced one pulse width apart and, as the wave passes, an rf signal is produced at the output whose phase is determined by the relative position of individual taps in the pair.

SAW devices, presently available, contain 100 to 200 taps, spaced 20 to 100 ns apart, and operate between 50 and 500 MHz. Insertion losses are typically 10 to 30 dB. Devices under development are expected to have over 1000 taps with less than 3 ns spacings and will be capable of operating at 1 to 2 GHz.

Although the pseudorandom coded signal with matched filtering increases sensitivity over the single pulse system, the recording bandwidth problem remains. The bandwidth requirements can be reduced by using either multiple or multiplex correlators for detection. Both techniques have been analyzed by Bello [1973], and the latter was selected for the ITS instrumentation (see section 4.3). A simplified block diagram of a multiplexed correlation system is shown in figure 11. Although a



(a) TRANSMITTER



(b) RECEIVER

Figure 9. Block diagram of matched filter system configuration.

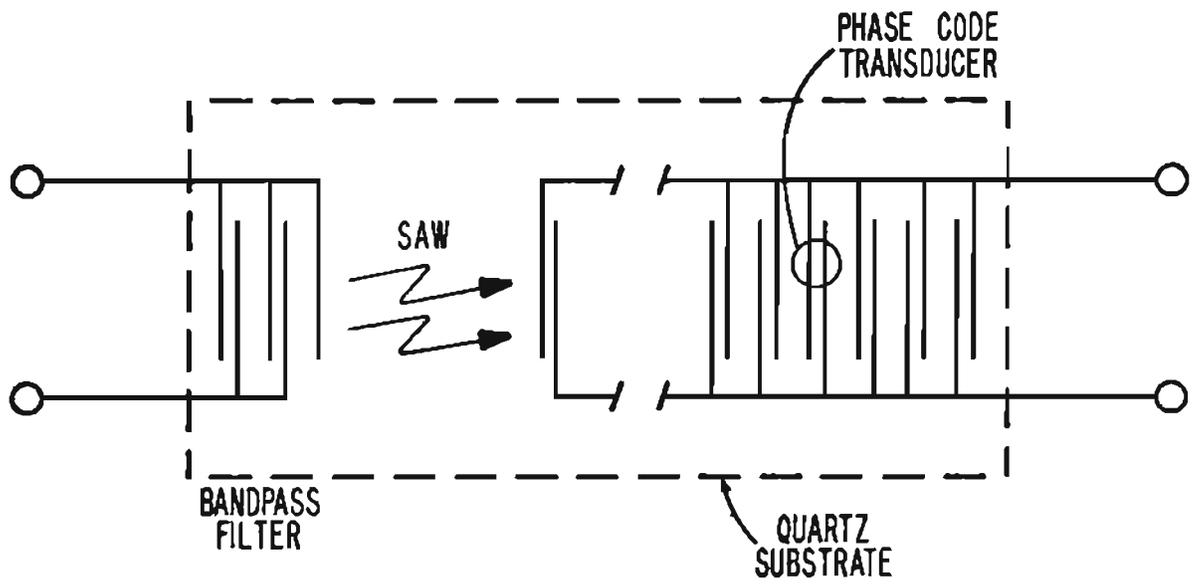
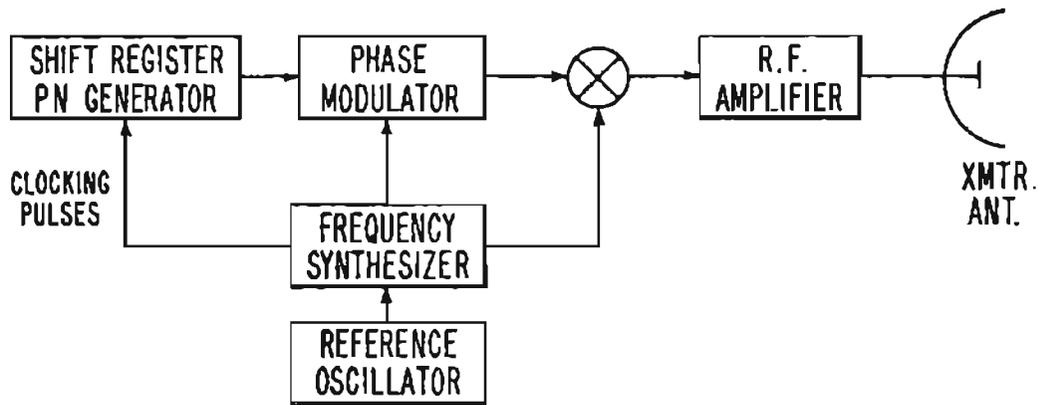
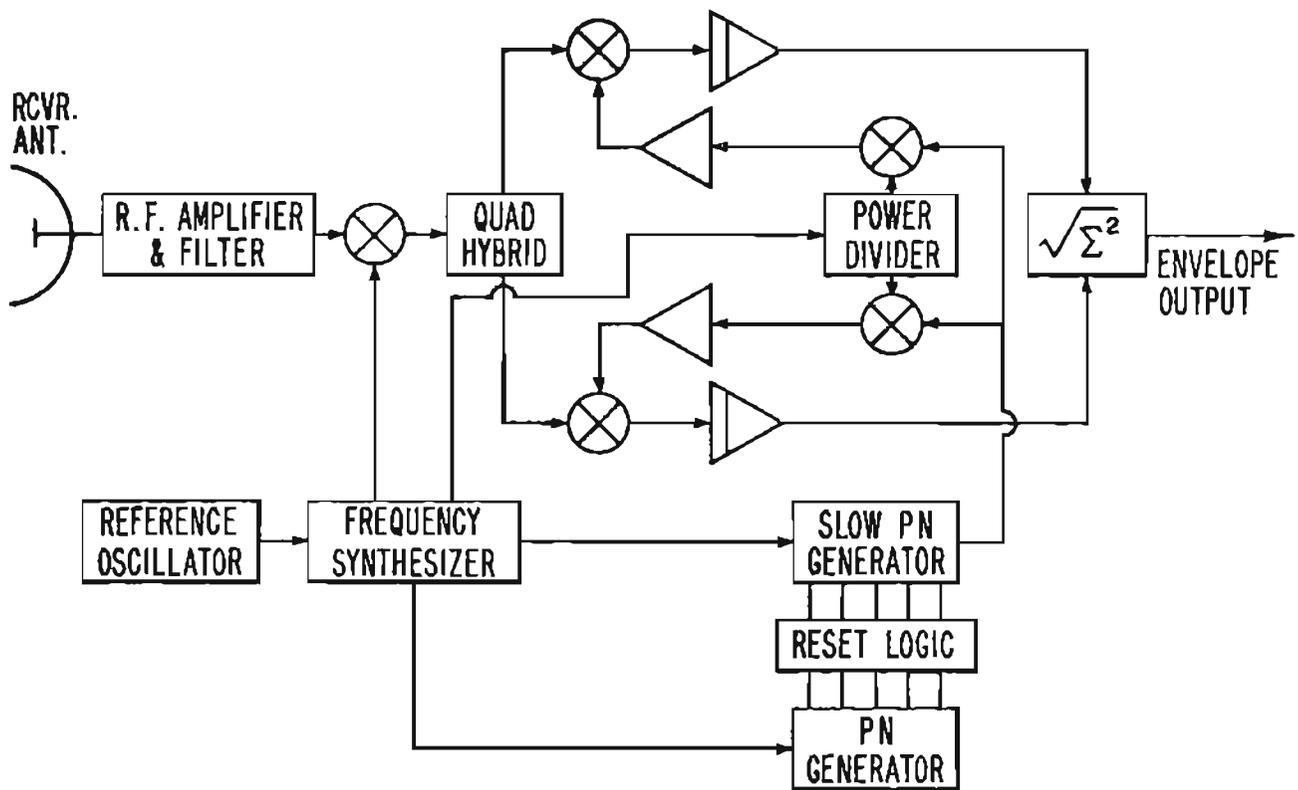


Figure 10. Schematic of interdigital transducer design for biphasic code surface wave devices.



(a) TRANSMITTER



(b) RECEIVER

Figure 11. Block diagram of multiplexed correlator system configuration.

tapped delay line device could be used for generating a pseudorandom signaling waveform, here the desired sequence is generated by shift registers. The shifting rate is determined by clock pulses from a frequency synthesizer. The reoccurrence rate of the sequence is determined by the number of shift registers. Example shift register sequence generators are shown in figure 12.

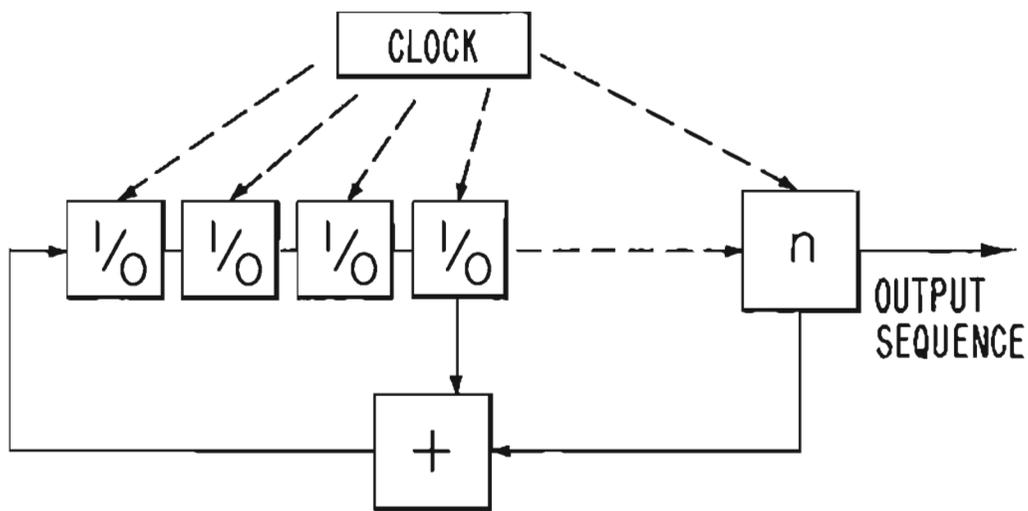
A maximum length sequence generator (figure 12a) of degree n consists of n consecutive binary storage units, a clock which shifts the state of each storage unit to the next, and two exclusive "or" feedback loops. The output is always ultimately periodic, repeating itself exactly at intervals of $\Delta T = (2^n - 1)\Delta\tau$, where n is the number of storage units (binary shift registers) and $\Delta\tau$ is the clocking period. With additional feedback logic as in figure 12b, the n stage register is capable of producing any periodicity between 1 and 2^n times the clocking period. Proper feedback logic for generating these sequences is given by Golomb (1964). Note, however, that sequences which are not maximum length may not meet all of the desirable randomness properties.

Rectangular waveforms produced by maximum length shift registers may be considered as pseudorandom in the sense that they do satisfy most randomness properties and their autocorrelation functions are similar to the autocorrelation of band limited noise (Golomb, 1964).

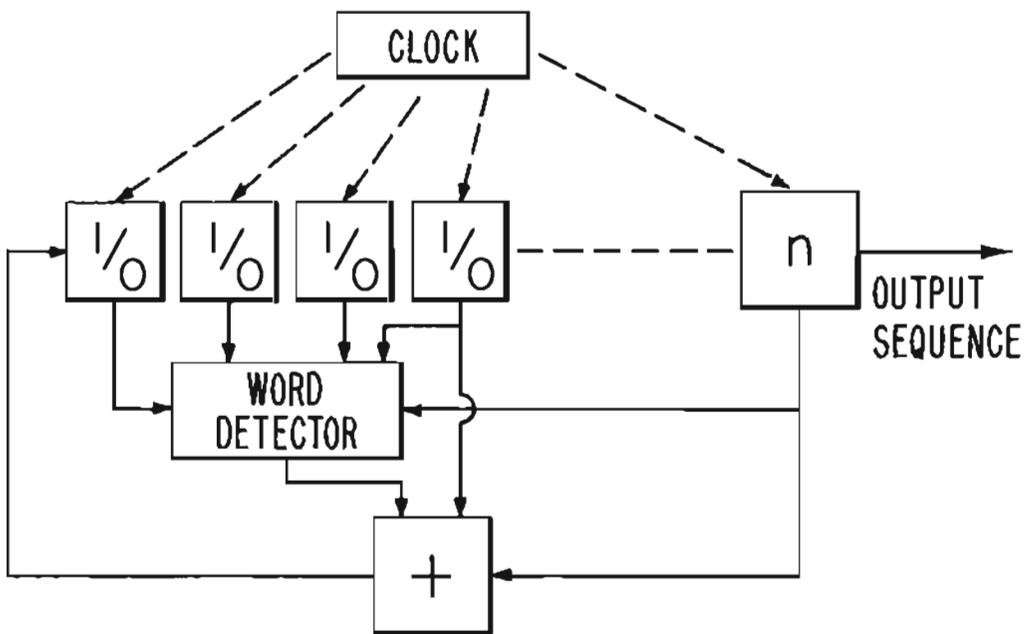
Figure 13 indicates the characteristics of a maximum length sequence generated by four stages of shift registers. Figure 13a is the binary sequence and figure 13b the rectangular waveform. The autocorrelation function given by equation (14) is drawn in figure 15c. The power spectrum is obtained by Fourier transform,

$$S(f) = \int_{-\infty}^{\infty} R(\tau) e^{-j2\pi f\tau} d\tau \quad (15)$$

$$= \left[\sum_{R=-\infty}^{\infty} 2^n \frac{\sin^2(\pi k/2^{n-1})}{(\pi k^2)} \delta(f - \frac{k}{T}) \right] - \frac{\delta(f)}{2^{n-1}} \quad (16)$$



(a) MAXIMUM LENGTH LINEAR SHIFT REGISTER



(b) ARBITRARY LENGTH LINEAR SHIFT REGISTER

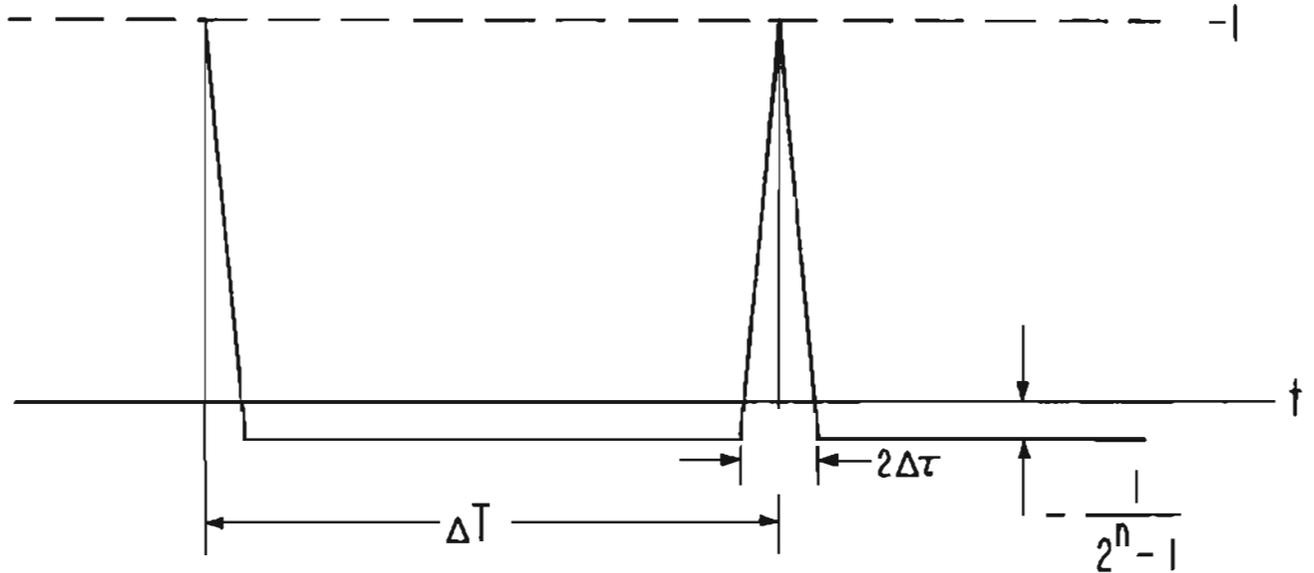
Figure 12. Pseudorandom sequence generators.

0 0 0 1 0 0 1 1 0 1 0 1 1 1 0 0 0 1 0 0 1 1 0 1

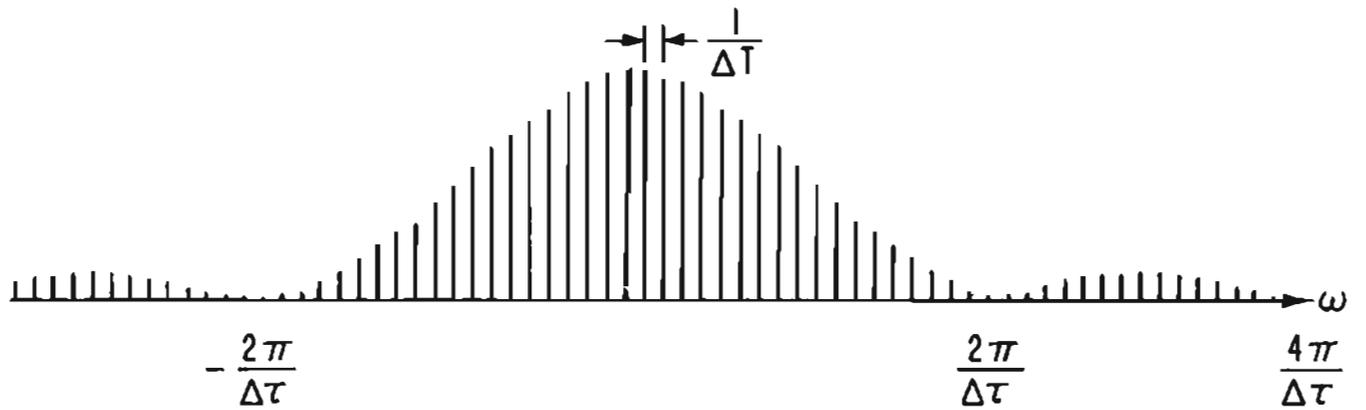
(a) BINARY SEQUENCE



(b) RECTANGULAR WAVEFORM



(c) NORMALIZED AUTOCORRELATION FUNCTION



(d) POWER SPECTRUM

Figure 13. Maximum length shift register sequence characteristics.

This power spectrum is a line spectrum with frequencies at multiples of the fundamental as shown in figure 13d.

The rectangular waveform modulates a carrier for subsequent transmission. At the receiver, the signal is detected and cross-correlated with a pseudorandom sequence generated in the receiver. Either several correlators operating with different delayed replicas of the signal or single correlators operating with multiplexed time delay replicas may be used. The example system shown in figure 13 is the multiplexed type. The multiplexed delay feature is achieved using two pseudorandom sequence generators with one clocked at a slower rate than the other. Comparison logic between the two generators provides a means for resetting the slow register to any desired observation period. In terms of actual path delays, this observation "window" must be large enough to include all of the delay responses, i.e., greater than the delay spread, L . Maximum window length cannot, of course, exceed the ambiguity window, ΔT .

The cross correlation function between two random sequences may be distorted when one is clocked at a different rate. This distortion, if excessive, may affect the accuracy of the channel impulse measurement. Distortion is a function of the different lengths of elements in the code. If one generator is clocked at frequency f_1 , and the other at $f_1 - \delta f_1$, then the element length of the slow clock is given by

$$T_2 = 1/(f_1 - \delta f_1) = 1/f_1 (1 + \delta + \delta^2 + \delta^3 + \dots) \quad (17)$$

$$T_2 \approx T_1 (1 + \delta) \text{ when } \delta \text{ is a small positive number.}$$

The difference in the recurrence period of the total sequence is therefore

$$T_1 (2^n - 1) - T_2 (2^n - 1) = \delta T_1 (2^n - 1), \quad (18)$$

where n is the number of stages in the shift register. For this difference to have a negligible effect on the cross-

correlation function, the largest time offset between the two sequences must be much less than an element duration. The largest offset occurs between the last elements. Therefore, the following inequality must hold:

$$\delta T_1 (2^n - 1) \ll T_1, \quad (19)$$

or

$$\delta \ll 1 / (2^n - 1).$$

For example, when $n=9$, then δ should be much less than 2×10^{-3} to minimize the distortion. With a 10 MHz clocking rate, it has been noted by Cox (1972) that the distortion is negligible when $\delta = 2 \times 10^{-4}$ and considerable when $\delta = 10^{-3}$.

Clocking the receiver generator at a slower rate changes the time scale (and bandwidth) of the cross correlation function by an amount $k = f_1 / (\delta f_1)$ and the base length of the function is $2k$ times the element length. For $f_1 = 10$ MHz, $\delta = 2 \times 10^{-4}$, $\Delta \tau = 0.1 \mu\text{s}$, $k = 5000$ and the base length is 1 ms.

The relative stability between IF outputs at the transmit and receive terminals can have undesirable effects such as a shift in the observed power spectra. Frequency instabilities introduce errors in the in-phase and quadrature components of the complex received signal. If severe, these instabilities can mask the phase variations which occur in the channel. A phase-locked system with a time constant which is large compared to the measurement intervals may be used to reduce or eliminate this effect.

There are obviously many other possible system configurations differing in concept and detail from the three shown here. For example, the matched filter detection scheme could be used with pseudorandom sequences generated by shift registers or correlation detection can be used on sequences generated by matched filter techniques. The multiple correlator receiver has certain advantages over the multiplexed system. Less time is required between response measurements, and the time varying response at different incremental delays are directly applicable as tap-gain functions for channel simulation purposes. The added complexity may not be warranted unless fast changes occur on

the path or real-time simulation using stored tap gain functions is desired.

In the following section some systems which have actually been implemented are reviewed with emphasis on the ITS system presently in use.

4. SYSTEM IMPLEMENTATION

Several impulse response measurement systems whose design is based on the different concepts presented have been implemented. These have been used to evaluate transmission channels for different bands in the spectrum and, therefore, have differing capabilities. Specific examples are summarized in the following subsections. One system was acquired in 1973 by ITS for developing a channel characterization program. This system with several design modifications and additions is described in detail in section 4.3.

4.1 Background

Pulse techniques have been in use since before World War II to measure characteristics of radio propagation paths. One widely used technique, the ionosonde, is described by Wright, et al. (1957). High frequency (HF) pulse transmitters are still used to sound vertically the ionosphere and to sound obliquely long distance paths between terrestrial terminals. The duration of the rf pulses used in these HF sounders is 10 μ s to 30 μ s long in order to resolve ionospheric propagation modes. Peak powers up to 200 kW were often used to provide system sensitivity.

DeLange (1952) at the Bell Laboratories, studied a line-of-sight channel using 1 watt pulses at 4 GHz with a pulse duration of 3 ns at half amplitude. He observed multipath transmission effects during fading periods indicating delay spreads of 7 ns over a 35 km path.

Waterson and others, in unpublished work at the National Bureau of Standards, developed a pulse type sounder in 1965

for the microwave region using 1 ns pulses at 9 GHz to study the bandwidth limitations of line-of-sight (LOS) tropospheric paths which excluded ground reflections. The multipath caused by atmospheric refraction occurred only a small percentage of the time when measurements were being made and decreased rapidly with elevation angle. The delay spread which did occur limited the bandwidth to 0.1 GHz over nearly horizontal paths (with possibly some ground reflection). Bandwidths exceeded 1.5 GHz at 2° elevation angles and above. Additional results obtained in Hawaii with this system are given by Skerjanec (1972).

A multiple correlator probe and channel analyzer based on the RAKE concept is also described by Bussgang, et al. (1976). The probe is designed to record tap gain functions over a VHF channel. These functions can then be played back in a stored channel simulator to reproduce the actual fluctuations of the channel itself rather than using statistically postulated sources. The probe transmits a 511 bit code and the analyzer consists of ten IF signals which are filtered and coherently demodulated in quadrature to provide 20 tap gains. These are then time-division multiplexed onto five tracks of a tape recorder for use in the future playback on the simulator.

When sensitivity requirements exceeded peak power limitations at the transmitter, noise-like probing signals and pulse compression techniques were employed. An HF sounder transmitting coded trains of rectangular waveforms and using a matched filter for reception is described by Coll and Storey (1964). Another example is the RAKE concept introduced by Price and Green at MIT (1958). The term RAKE covers a broad class of communication techniques which use wideband signaling and reception to combat the effects of multipath and fading by sounding the channel. Initially, RAKE was developed to reduce the effects of frequency selective fading and intersymbol interference on HF links. The basic concept was later applied by Bitzer, et al. (1966) and Barrow, et al. (1969), of Sylvania to troposcatter channels operating around 900 MHz. Detailed multipath resolution was obtained by transmitting a wideband signal structure using pseudorandom binary sequences which phase

modulated the carrier. At the receiver, a set of delay replica of the transmitted waveform was correlated with the received signal to give a continuous estimate of the received signal amplitude and phase corresponding to a particular time delay. The correlation process was performed for many consecutive time delays to yield the multipath structure.

A multiplexed correlator probe developed by Bell Laboratories was used by Bailey (1970) to characterize the troposcatter channel at 2 GHz. A similar type sounder was used by Cox (1972) to study multipath propagation at 910 MHz in a mobile radio environment. Two correlators were used to measure the in-phase and quadrature components of the impulse response. The phase keyed pseudorandom reference signal was swept by the incoming signal to produce an analog output signal proportional to the true impulse, but scaled in time. This is the type of sounder acquired by ITS. A block diagram of the system was shown in figure 11. A nine stage shift register was used for generating a 511 bit pseudorandom sequence at a 10 MHz clocking rate. Thus, the system resolution was approximately 200 ns.

The wideband pseudo-random noise (PN) sequence modulates a 70 MHz IF signal derived from the same stable 5 MHz source that is used to clock the PN generator. This signal is mixed to the desired carrier frequency and transmitted as a single sideband signal. At the receiver, the local oscillator frequency is derived in the same manner as at the transmitter from another stable 5 MHz source. The 70 MHz IF is processed by in-phase and quadrature phase correlation detectors. The correlation functions obtained are squared and combined to form the equivalent lowpass impulse response of the channel. The 511 bit sequence is correlated over a variable length window established by comparing a local reference PN generator with a similar generator clocked at a slower rate.

Table 3 summarizes the pertinent features of the basic kinds of systems discussed above.

Reference	DeLange (1952)	Price & Green (1958)	Coll & Storey (1964)	Watterson, et al (1965)	Bitzer, et al (1966) Barrow, et al (1969)	Bailey (1970) Cox (1972)
Organization	Bell Labs.	MIT	DRTE	ITS	Sylvania	Bell Labs.
Applications	Tropo-LOS	HF Comm.	HF Prop.	Tropo. Prop.	Troposcatter	Troposcatter LOS Tropo.
Frequency Band	4 GHz	8-17 MHz	2-24 MHz	9 GHz	910 MHz	2 GHz and 910 MHz
Probing Signal	Short Pulse	PN sequence	Impulse Equiv.	Short Pulse	PN sequence	PN sequence
Single Pulse Width	3 ns	8 μ s	25 μ s	1 ns	100 ns	100 ns
Code Length	not appl.	1023	17	not appl.	511	511
Recurrence Rate	10 MHz	120 kHz	40 kHz	10 MHz	~20 KHz	~20 kHz
Modulation Scheme	AM	FSK+90 Hz	AM & PSK	AM	PSK	PSK
XMTR Power	unknown	20 kW	unknown	10 W	5-10 kW	10 W
Detection Scheme	Envelope	Correlators	Matched Filter	Envelope	Multiple Correlators	Multiplex Cork
Number of Taps	-1	20	2	-1	20	2
Tap Spacings	not appl.	10 μ s	25 μ s	not appl.	0.1 μ s	0.1 μ s
Recorder/Display	Oscilloscope	--	Oscilloscope	Oscilloscope	Chart Record	Chart Record
Max. Delay Spread	\approx 10 ns	8.5 ms	3 ms	100 ns	> 5 μ s	50 μ s
Min. Resolution	3 ns	10 μ s	25 μ s	1 ns	0.1 μ s	0.1 μ s

Table 1. Summary of characteristics of some pulse sounding systems.

4.2 The Present ITS System

Since acquiring the impulse response measurement system as described by Cox (1972) from Bell Laboratories, ITS has made extensive modifications to increase measurement capabilities. Other modifications are in the process of being implemented or are planned. The system as presently constituted is reviewed below.

The principal modifications include:

- a) increasing operating frequency range to the microwave region;
- b) increasing clocking rate to 150 MHz;
- c) providing for doubling the pseudo-random code length to increase sensitivity;
- d) adding phase lock capabilities to improve stability;
- e) duplicating correlators in receiver to permit dual channel operation for diversity measurements.
- f) providing for error rate detection of code elements for performance measurements;
- g) considerably reducing size and weight to increase portability.

Block diagrams of major sections of the ITS system are shown in figures 14-16. At the transmit terminal (figure 14), the 5 MHz reference oscillator frequency is multiplied to a 600 MHz IF which can be phase shift keyed by the PN generator output. This modulated IF is then mixed and filtered to produce a modulated carrier. A 10 watt (peak power) traveling wave tube (TWT) power amplifier is normally used to drive the antenna transmission line to the antenna feed.

The PN generator produces the pseudo-random sequence using either a 9 or 10 stage shift register. The code sequences consist of 511 code elements. At a typical 150 MHz clocking rate, each code element is approximately

6.7 ns. The total sequence repeats every 3.4 μ s for the 511 code.

The front-end portion of the dual channel receiver is shown in figure 15. These system components are packaged in a watertight enclosure which is normally located in close proximity to the two antennas. Output from this enclosure consists of two 600 MHz IF signals. The rf to IF conversion circuitry is derived from a 100 MHz input signal. A separate PN generator and mixer circuit is also located in this antenna box for calibration purposes. Programmable attenuators in series with each antenna terminal can be selected remotely to insure proper operation within the dynamic range of the receiver system and to calibrate the system. A simplified block diagram of the receiver processing section is given in figure 16. The slow PN generators drift rate can be varied using an external frequency synthesizer. This slow PN generator output is converted to a PSK signal at IF and cross-correlated in quadrature with the received signal to produce in-phase and quadrature components of the response. These quadrature components of the response are integrated, squared and summed to produce the power delay profile scaled in time.

Since the transmitter and frequency standards may drift slowly with respect to each other, the measured phase may not be absolute. Slow drifts may be corrected by the phase lock loop circuitry shown in the upper portion of the block diagram.

In applications where it is desirable to measure and record received signal level, the output of the IF amplifier is fed to a power meter, a log converter, and a recorder.

Dual channel operation is incorporated in the system for redundancy and for certain special applications. One application for the two processing channels is discussed in the following section.

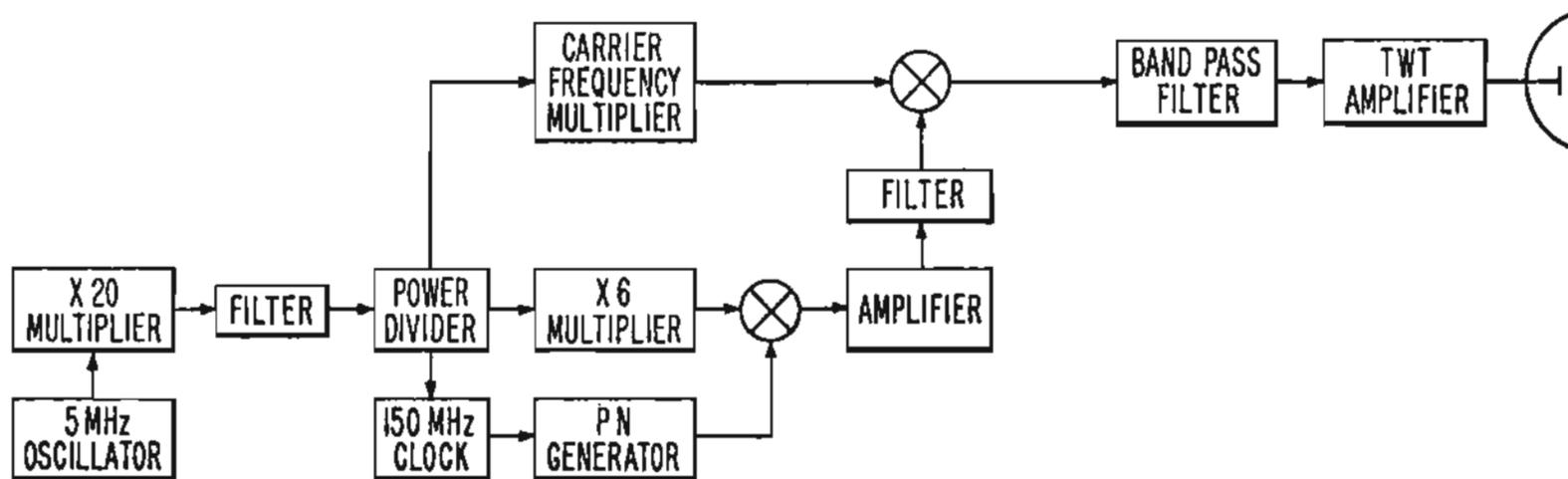
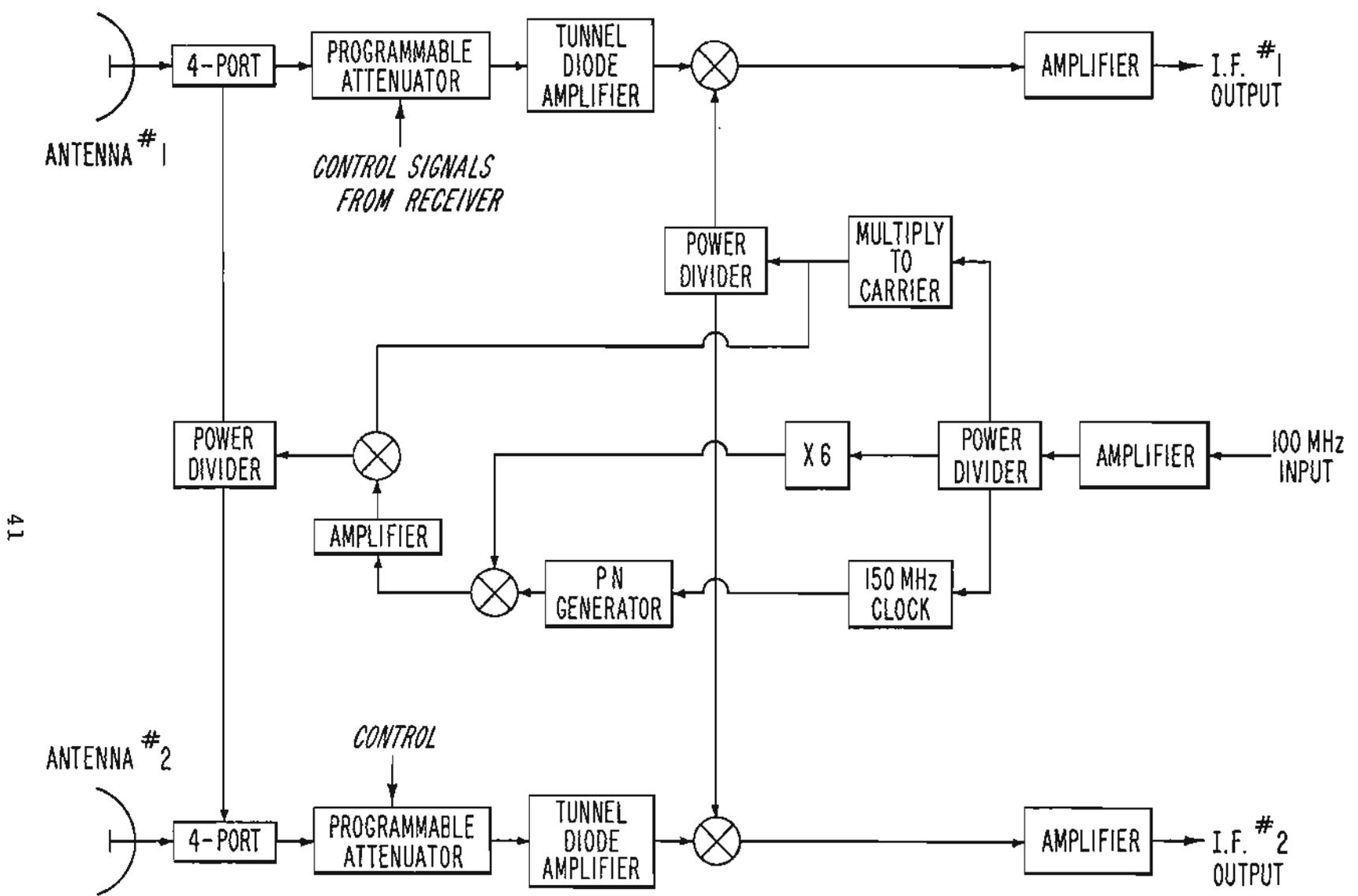


Figure 14. ITS system - transmit terminal.



41

Figure 15. ITS system - receiver front end.

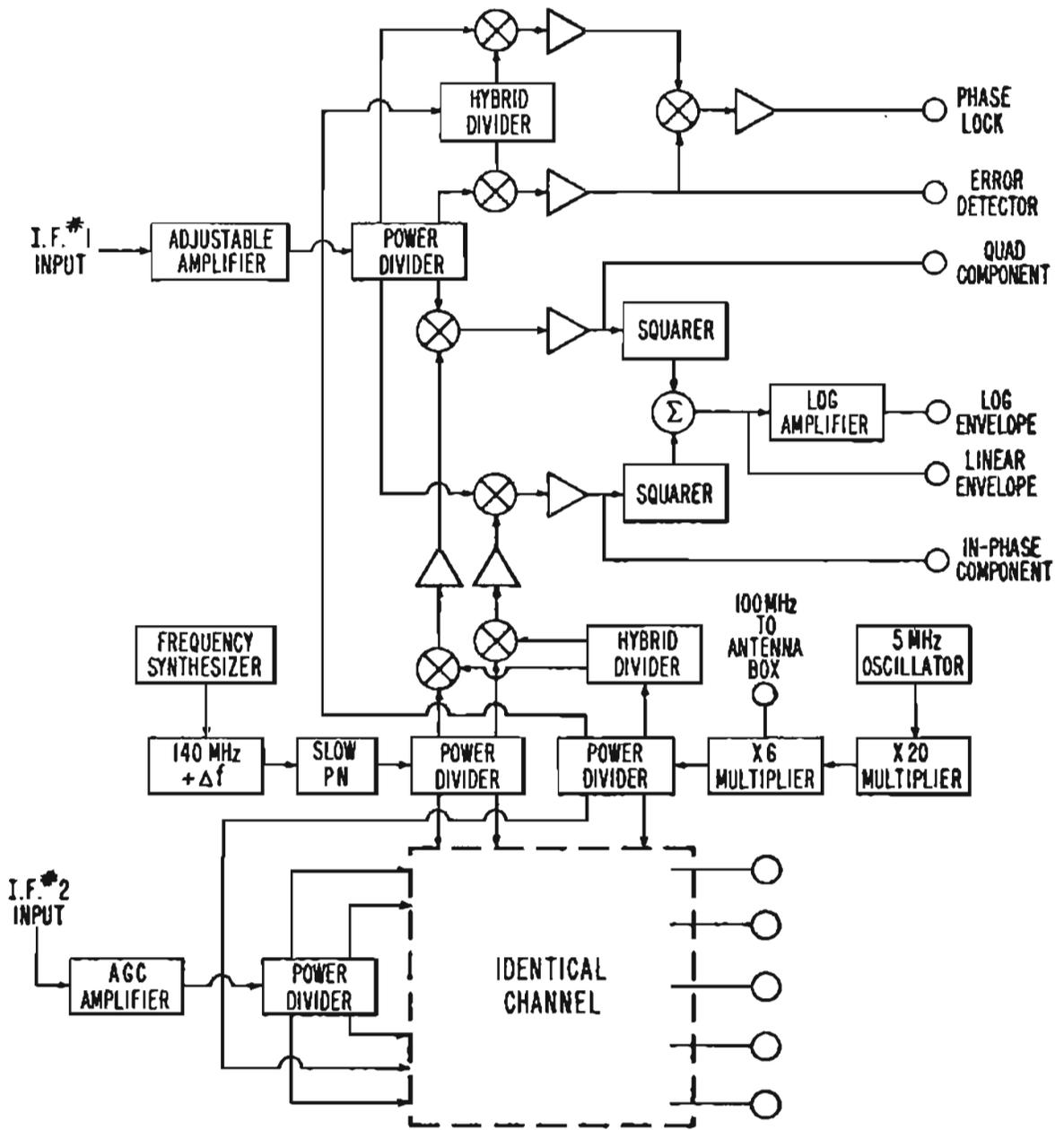


Figure 16. ITS system-signal processor.

4.3 Applications, Examples of Results, and Future Plans

The ITS system has been operated in various modes and frequency bands over the past year to accomplish these tasks:

- a) to measure multipath reflections which exist near an active airport terminal runway to assist in evaluating propagation effects on microwave landing systems;
- b) to relate multipath structure to meteorological conditions on an experimental link in Hawaii;
- c) to evaluate potential sites for digital links in Europe by measuring multipath vs. height of antennas and pointing angle.

Some examples of the Hawaii experiment are shown in figure 17. These data were obtained at 8.6 GHz over a 120 km LOS path over water between fixed terminals on the islands of Maui and Hawaii. In this region, warm, moist air layers are formed at low altitudes. As these inversion layers rise between the terminals, refraction occurs causing multipath interference. Resolvable delay differences observed varied from a few nanoseconds up to 20 ns. Occasionally, two delayed components were present. The maximum rate of delay variation observed was 25 ns/s. These data were obtained with the system operating with a 150 MHz clocking rate. Responses were recorded on magnetic tape and results replotted in the laboratory using a computer processor.

The five functions displayed were measured sequentially over a period of approximately 10 s (2 s between each function). The data were obtained during a period of time when distinct multipath components existed both within and beyond a bit-length in delay time due to atmospheric layering in the propagation path. The multipath components were moving from short delay times to longer delays (left-to-right motion in the figures). The data were measured on March 18, 1974 at approximately 1500 hours HST. Responses depicted in figure 17a through 17c are described below:

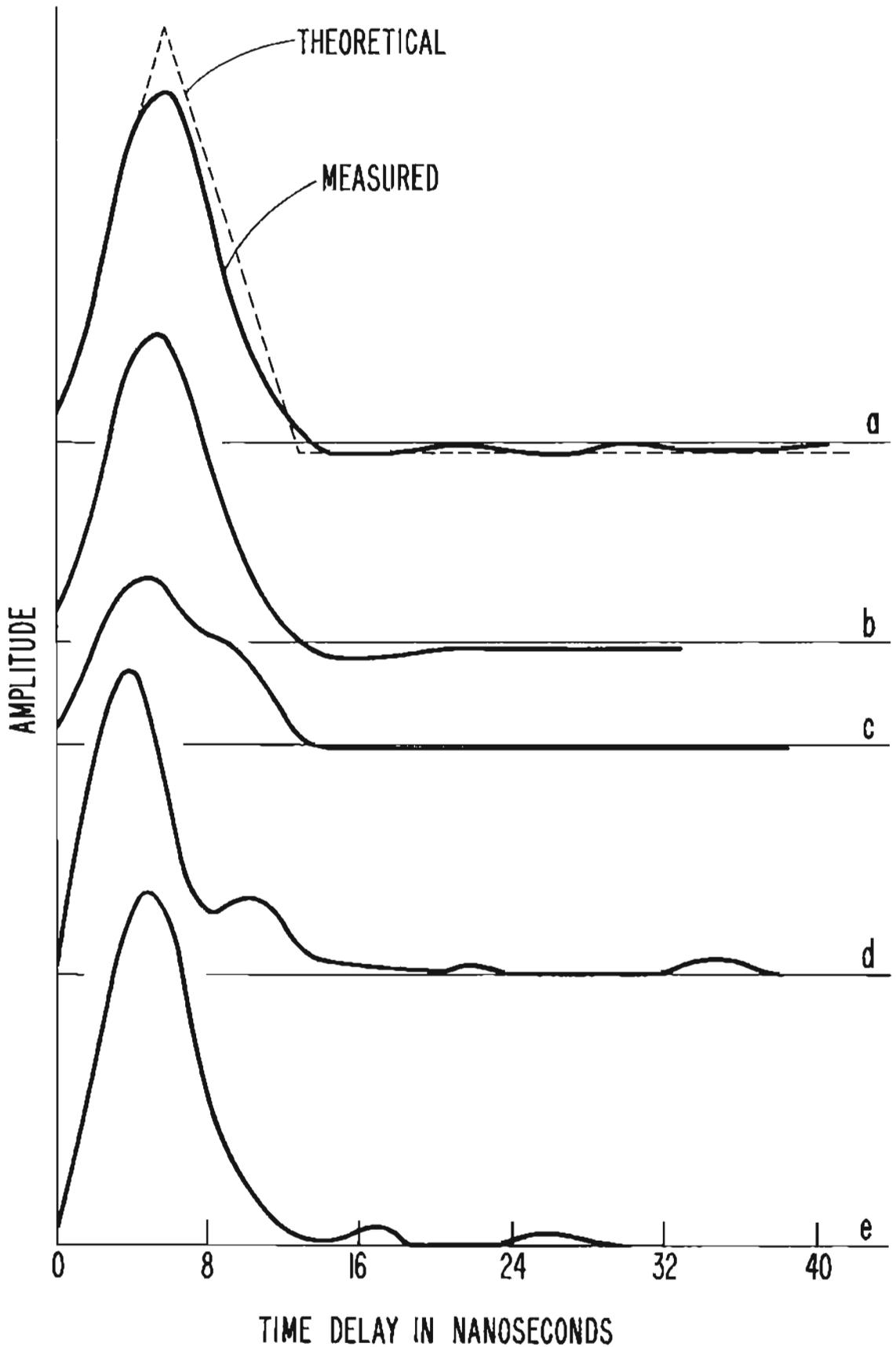


Figure 17. Impulse response between Haleakala and Kona, Hawaii, March 18, 1974 at 2 second intervals.

a) This response represents a clear-channel condition; little or no multipath activity is visible. The theoretical correlation (impulse) function has been drafted over the measured response for comparison.

b) This impulse illustrated the first evidence of a multipath component within a bit time (6.66 ns). Comparison with a) indicates a distortion to the trailing edge of the impulse, and a lower magnitude indicating a fade in power level.

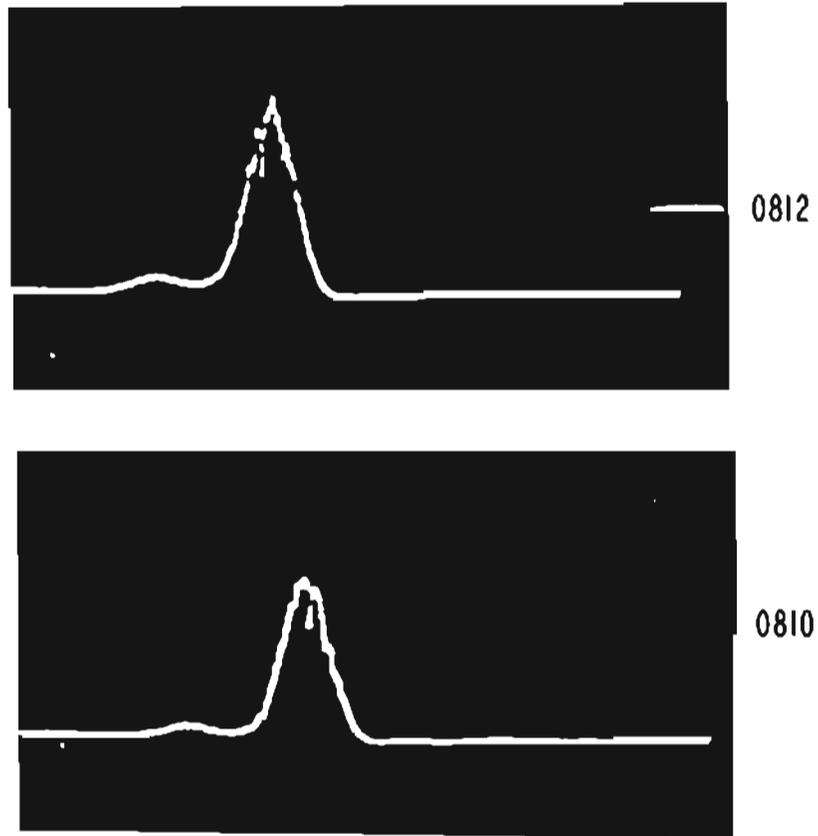
c) The multipath component has moved to a longer delay time, causing more distortion to the response function, and is almost identifiable as a separate response.

d) The multipath component has moved farther in delay time, becoming a distinct response within the bit-time. Note additional small multipath components at delays greater than a bit time.

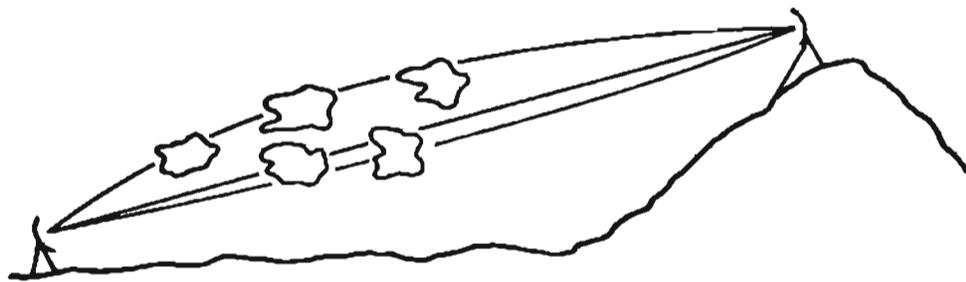
e) The component that was within a bit time in d) has now moved to a delay on the order of 16 ns. Another component is also distorting the direct component.

Following this sequence, the next response function returned to that illustrated in a). This was typical of the magnitude and motion of the atmospheric multipath components during the measurement period. Direction and rate of motion of the multipath varied over the experimental period.

The data obtained in Hawaii can be attributed to a relatively stable atmospheric multipath where a small number (one or two) of secondary reflected or refracted signals occur simultaneously with the desired signal. Another somewhat different phenomenon was observed during the path test program conducted for the U.S. Air Force over a 106 km path in northern Italy. Two responses obtained in the early morning between Aviano and Mt. Venda, Italy, are shown in figure 18a. The high-frequency components observed on each response are attributed to signals arriving via many different paths. The multipath components are caused by



(a) OSCILLOSCOPE PHOTOGRAPHS OF IMPULSE RESPONSE (6.7ns/cm)



(b) ATMOSPHERIC TURBULENT MULTIPATH

Figure 18. Mt. Venda to Aviano (Italy) path test measurements, September, 1975.

turbulent atmospheric effects along this path, as suggested by the sketch in figure 18b. Although the equipment was not capable of discerning each individual path, the combined effect is observable by distortion of the responses. The oscilloscope photographs indicate signal delays sometimes less than 1 ns. Although the two photographs shown were taken two minutes apart, the responses observed at 1 s intervals show similar differences. These kinds of data, along with received signal level measurements and meteorological data, yield valuable insight into propagation effects occurring on the link.

The ITS channel probe has potential applications in several areas. It has already been demonstrated as an ideal system for path testing. It is easily installed and convenient to operate. The processing gain achieved with correlation detection simplifies weak signal detection and, therefore, aids in the initial antenna alignment procedure which usually is a time consuming process. Also, when the impulse responses observed over a link show that no ground reflections exist, the need for detailed height gain profiles for antenna positioning and diversity reception is alleviated. Even when ground reflections are observed it appears that it may be possible to predict height gain profiles using certain simplifying assumptions. Further work is needed, however, on this aspect to evaluate procedures.

As more response functions are collected over a variety of links and under different environmental conditions, a data base for representative channel characteristics will be developed. Such a data base will be useful in developing channel simulators for communication system design and performance evaluations.

Another possible future use for the channel probe is discussed in the following paragraphs:

Currently there is a great interest in the possibility of using cross-polarized radio transmissions in line-of-sight links to double the channel capacity using orthogonal antenna polarization at the same frequency. This frequency re-use concept appears feasible, but is dependent upon the

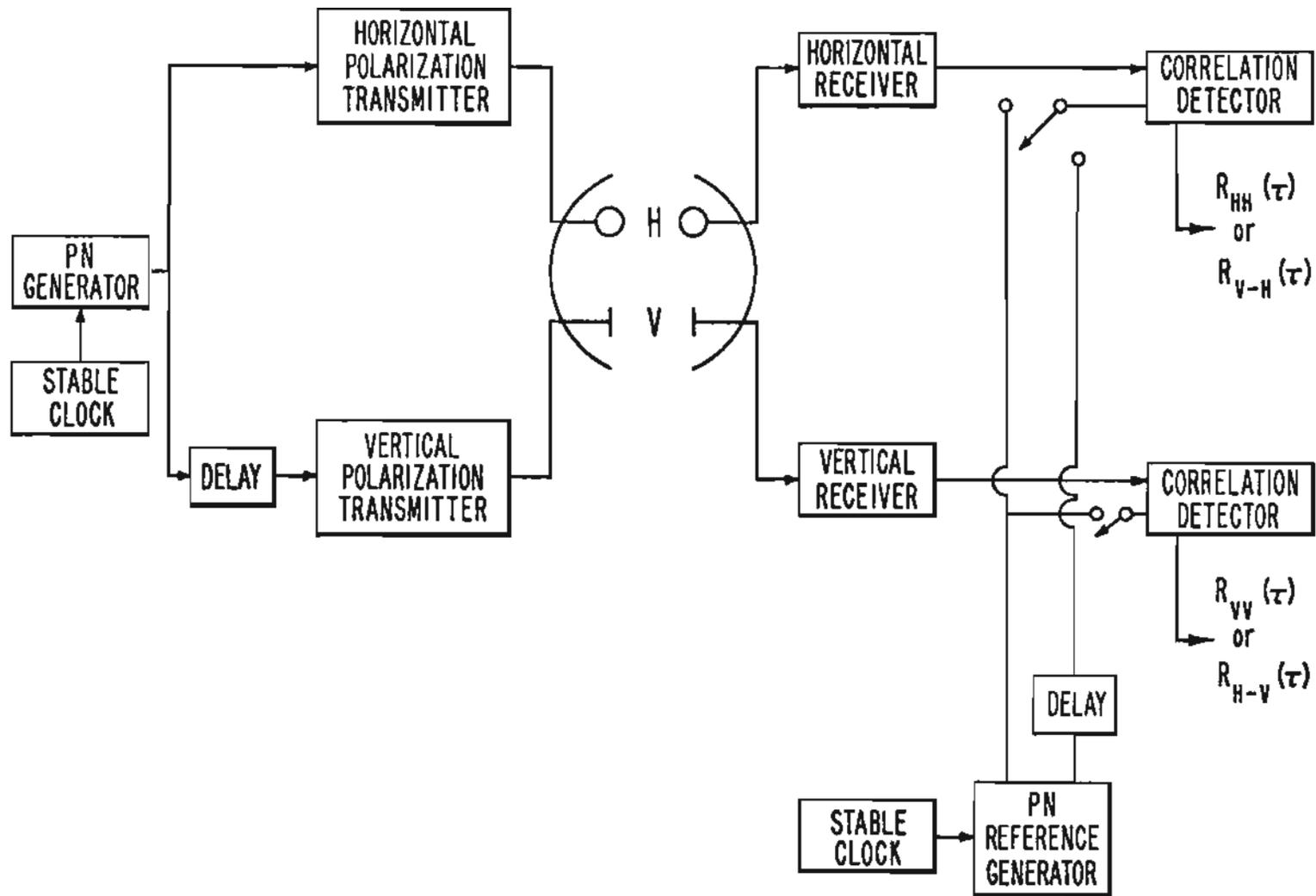


Figure 19. Concept for cross-correlation measurement.

isolation that can be achieved in practice. One method for measuring depolarization effects on a channel using the ITS system is depicted in figure 19. A direct and a delayed version of the same PN signal is transmitted on two polarizations by the transmitter. The receiver is configured with two local PN reference signals with a relative delay the same as at the transmitter.

In this configuration, a choice of local reference can be made at the receiver for each channel. For example, if the direct PN signal is placed on the horizontal polarization as indicated in figure 19, correlation with the direct reference source in the receiver will yield the normal impulse response from $R_{HH}(\tau)$. If the delayed PN reference is used for the correlation detector instead, the resulting function becomes $R_{H,V-H}(\tau)$, or the depolarized function from the vertical channel. This is the only function possible from the measurement since $R_{HV}(\tau)=0$, as established at the transmitter. *

In like manner, the other depolarized function, $R_{V,H-V}(\tau)$, can be detected from the vertically polarized channel by selecting the non-delayed (or direct) reference source in the receiver. As a result, the depolarized component from each of the cross-polarized transmission channels could be developed simultaneously and independently with no ambiguities.

An added option to this technique is quite straightforward from figure 19. The receiver can be implemented with two correlation detectors for each channel, one used to develop the desired-channel impulse response function and the other simultaneously used to detect the depolarized component. Such a configuration doubles the number of required detectors (which would be in parallel), and the two (direct and delayed) reference sources in the receiver. The advantage would be the simultaneous data feature, and with proper calibration, it would be possible to restore the complete impulse response function for the cross-polarized system. For example, the two developed in each receiver channel could be added together in real time to produce the horizontal or vertical channel functions.

*The subscripts H and V indicate horizontal and vertical polarization functions. The notation H-V or V-H is used to indicate the depolarized components.

A very significant advantage may be derived from this latter technique toward isolating depolarization effects due to different aspects of the propagation channel. For example, it is conceivable that if one observes the depolarized impulse function at τ near zero and finds a response, this portion of the function will depict depolarization due to rain or other scintillation effects along the direct path. In a multipath situation, the reflected energy will normally arrive later at the receiver antenna. Thus, any discernable response at $\tau > 0$ in the depolarization function should reflect depolarization effects at the multipath reflection point(s).

5.0 CONCLUDING REMARKS

The transmission characteristics of any medium whether it be a passive filter or a time-varying radio propagation channel can be specified by the frequency response or its inverse Fourier transform, the impulse response. Techniques for measuring the impulse response have been reviewed with emphasis on using pseudo-random signals and correlation detection. One system using a maximum length shift register for signal generation and a time multiplexed correlator for detection is employed by ITS to obtain complex bandpass response functions over microwave links. These sample functions, however, contain too much information to conveniently characterize a channel. Additional processing is required to statistically describe signal distortion in a manner which can be usefully related to communication system performance. Thus, there is a need for developing computer analysis routines for reducing collections of impulse response functions to a few meaningful parameters and for evaluating these parameters by comparing them with measures of performance (error rate, for example) over the same channel. Sensors installed on the path to measure meteorological parameters would aid in determining the propagation mechanisms involved. This combination of response, performance, and meteorological data taken simultaneously on a channel would provide a better understanding of the effects of that channel on various modulation techniques and signaling rates. The ultimate goal is to characterize many different types of channels and thereby provide an engineering data base for the systems designer developing advanced telecommunication links.

REFERENCES

- Baily, C.C. (1970), Characterization of troposcatter channels by impulse response measurement, AGARD Conference Proceedings, Part II, 39-1 to 39-11.
- Barrow, B.B., L.G. Abraham, W.M. Cowan, and R.M. Gallant (1969), Indirect atmospheric measurements utilizing rake tropospheric scatter techniques, Part I, Proc. IEEE 57, No. 4, 37-551.
- Barsis, A.P., R.A. Norton, and P.L. Rice (1962), Predicting the performance of tropospheric communication links singly and in tandem, IRE Trans. Comm. Syst., CS-10, No. 1, 2-22. Washington, DC.
- Bello, P.A., J.K. DeRosa, and C.J. Boardman (1973), Line-of-sight wideband propagation, Air Force Systems Command, Rome Air Development Center Report RADC-TR-73-167, May.
- Bitzer, D.R., D.A. Chesler, R. Ivers, and S. Stien (1966), A rake system for tropospheric scatter, IEEE Trans. Comm. Technol. COM-14, No. 4, 499-506.
- Bullington, K. (1971), Phase and amplitude variations in multipath fading of microwave signals, BSTJ 50, No. 6, 2039-2053.
- Bussgang, J.L., E.H. Getchell, B. Goldberg, and P.F. Mahoney (1976), Stored channel simulation of tactical VHF radio links, IEEE Trans. Comm. Technol. COM-24, No. 2, 154-163.
- Coll, D.C., and J.R. Storey (1964), Ionospheric sounding using coded pulse signals, Radio Sci. J. Res. 680, No. 10, 1155-1159.
- Cox, D.C. (1972), Delay doppler characteristics of multipath propagation of 910 MKz in a suburban mobile radio environment, IEEE Trans. Ant. Prop. AP-20, No. 5, 625-628.
- Craft, H.D. (1971), Attenuation statistics at 15.3 GHz for Charlsburg, Md., COMSAT Technical Review 1, No. 1, 221-225.

- DeLange, O.E. (1952), Propagation studies of microwave frequencies by means of very short pulses, BSTJ 31, 91-103.
- Dougherty, H.T. (1968), A survey of microwave fading mechanisms, remedies and applications, Nat'l Tech. Info. Service (NTIS Access No. COM-71-50288), Springfield, VA 22161
- Frank, R.L. (1963), Polyphase codes with good non-periodic correlation properties, IEEE Trans. Inform. Theory IT-9, No. 1, 43-45.
- Gallager, R.G. (1964), Characterization and measurement of time & frequency-spread channels, Technical Report 352, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA.
- Golomb, S.W. (1964), Digital communications with space applications, (Prentice Hall Inc., Englewood Cliffs, NJ).
- Hubbard, R.W. (1971), Characterization of multiplicative noise in propagating systems, IEEE Electromagnetic Compatibility Conference Record, Tucson, Arizona, November.
- Huffman, D.A. (1961), The generation of impulse-equivalent pulse trains, IRE Trans. Inform. Theory IT-8, No. 5, 510-516.
- Kailath, T. (1962), Measurements on line-variant communication channels, PGIT No. 8, 5229-5236.
- Norton, K.A., P.L. Rice, H.B. Janes, and A.P. Bursis (1955), The rate of fading in propagation through a turbulent atmosphere, Proc. IRE 43, 1341-1353.
- Price, R., and P.E. Green, Jr. (1958), A communication technique for multipath channels, Proc. IRE 46, 555-570.
- Samson, C.A., and R.S. Kirby (1973), Observed 7 to 8 GHz signal attenuation during rainfall, IEEE Trans. Comm. Technol. COM-21, No. 7, 862-863.

Schwartz, M., W.R. Bennett, and S. Stein (1966),
Communication systems and techniques, Inter-University
Electronics Series 4, (McGraw-Hill Book Co.).

Skerjanec, R.E. (1972), Data results on nanosecond pulse
propagation measurements over line-of-sight paths,
Office of Telecommunications, Research & Engineering
Report 37.

Wright, J.W., R.W. Knecht, and K. Davis (1957), Annals of
the international geophysical years, III, Part 1,
(Pergamon Press).

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