

Binary Data Transmission Techniques for Linear Systems*

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Summary—The linearity and highly stable frequency characteristics of modern single-sideband equipment make possible improvements in the frequency spectrum utilization and performance of binary data transmission systems.

Problems associated with fully utilizing the binary data transmission potential of an SSB voice channel are discussed. These problems include consideration of frequency and phase stability of the SSB equipment and the propagation media, multipath reception of signals, delay distortion within the voice channel, maximum performance in the presence of noise, and maximum spectrum utilization.

Equipment designed to transmit 3000 bits per second over a SSB voice channel is described. Comparative performance data with standard systems are included.

RECENT DEVELOPMENTS in radio communication systems permit a change in data transmission philosophy, allowing the system design to be primarily concerned with the propagation media without the many compromises previously required to accommodate the deficiencies of the associated radio equipment.

In particular, recent advances in single-sideband transmission techniques provide practical radio circuits of greatly improved linearity and frequency precision. Oscillators with stabilities of approximately 1 part in 10^8 per day are in use, linear amplifiers providing high power with low distortion have been designed, special filters have been developed for sideband separation, and methods have been devised to stabilize the heterodyne frequencies by locking them to precision oscillators.

Single-sideband systems can now provide a linear communication link between two points, and the precision oscillators make it possible to establish time and frequency synchronization at both terminals, permitting the use of improved methods of binary data transmission.

Of the many factors governing the choice of modulation methods for long range high frequency (hf) communications the following are among the most important:

- 1) Performance in noise and interference.
- 2) Ability to work through multipath.
- 3) Spectrum conservation.

All three of these are improved by narrowing the received band to a minimum consistent with the information content and coding of the transmitted information.

The nature of binary transmission is such that the only information which needs to be transmitted is that of MARK or SPACE for each element, since the length

of time, shape, or nature of each element is pre-established for a given system. Binary information may be encoded in the plus or minus variations of a single parameter of the signal. The object of the receiving terminal therefore need be only to determine whether a MARK or SPACE has been transmitted.

Optimum filtering of a pulse in the presence of white noise is obtained by multiplying the pulse by a stored weighting function identical in form to the transmitted pulse and coincident with it in received time. Integration of this product over the period of the weighting function yields a result proportional to and having the sign of the transmitted pulse.

Weighting functions most commonly used are those of LC or mechanical filters and necessarily only approximate the desired form. W. H. Wirkler has suggested¹ kinematic and hybrid kinematic and dynamic methods for construction of the receiving weighting function.

The use of kinematic filtering methods provides the designer with complete control of the weighting function. This control has been used to provide matching of the incoming signal for performance in noise and to provide nominally zero crosstalk between properly placed keyed tones in a frequency division system. This allows the construction of practical equipment capable of approaching closely both the theoretical transmission limit of $2B$ measurements per second in band B and the theoretical limit for performance in white noise.²

In the system to be described, information is encoded in the transmitted signal in the form of phase reversals or lack of reversals between subsequent elements of a pulse train.³ A gated resonator is used to accumulate and properly weight plus and minus contributions of the received signal within each pulse. The relative phase of adjacent pulses is obtained by comparing the after-rings of a pair of resonators storing these pulses.⁴

High frequency SSB signals suffer distortion resulting from multipath and from unequal delays across the pass band of the sideband separation filters. To cope with this distortion it is necessary to transmit pulses which are long compared with the distortion expected. Typical hf

¹ An unpublished paper of W. H. Wirkler (April 12, 1949) discussed detection methods applied to telegraph signaling.

² B. M. Oliver, J. R. Pierce, and C. E. Shannon, "The philosophy of pcm," *Proc. IRE*, vol. 36, pp. 1324-1331; November, 1948.

³ M. L. Doelz, "Special Techniques for Detection in Noise," *Collins Eng. Rep. (CER-W272)*, Burbank, Calif., presented at IRE Subsection, Monmouth County, N. J.; January 21, 1953.

⁴ A. A. Collins, "Predicted Wave Signalling-Kineplex," presented at IRE Section, Dallas, Texas; December 16, 1954.

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multipath distortions of 1 to 3 milliseconds make pulse lengths of 10 to 20 milliseconds desirable.

Where the radio frequency channels are restricted to a relatively narrow bandwidth, as is the case in hf and wire line systems, frequency division multiplexing offers the greatest data carrying capacity by minimizing the required guard bands at the channel edges, while synchronous detection within the band permits close spacing and independent separation of the multiplexed tones.

A binary communication system has been designed based on these ideas, capable of providing 3000 bits per second of data in an SSB voice channel. The name Kineplex has been adopted for the system because of the kinematic aspect of the filtering and detecting process. The receiving equipment has stored in it detailed information as to the form of the expected signal. This information is used in the detection process to an extent consistent with the characteristics of hf propagation. Data is transmitted by means of multiple tones in the voice band, each tone carrying two independent sub-channels. A separate tone is transmitted to provide synchronizing information.

Information is contained in the relative phase of two adjacent pulses (Fig. 1). Subchannel 1 is carried as a

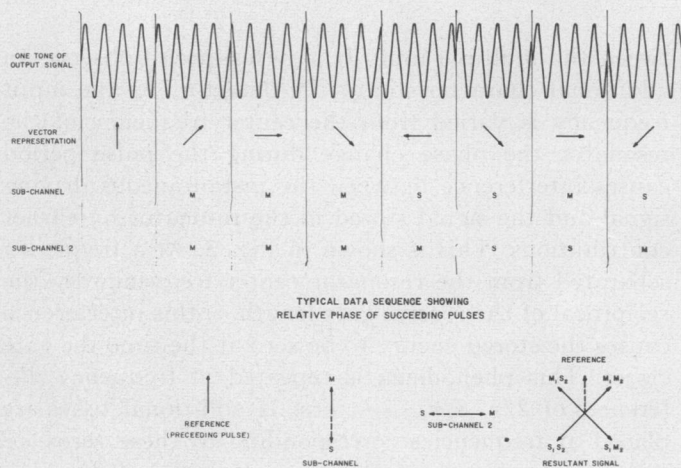


Fig. 1—Phase coding scheme.

phase reversal between adjacent pulses (0° for a MARK and 180° for a SPACE). The second subchannel is carried in a 90° , or quadrature, relation to the first ($+90^\circ$ for a MARK and -90° for a SPACE). The resultant signal has an amplitude of $\sqrt{2}$ times either sub-channel and one of the four possible values of phase shown. The output signal for one or for two channels is a tone of constant center frequency with phase discontinuities occurring between pulses. Twenty tones, at different frequencies, are multiplexed to provide the 3000 bit per second capacity. The frequency spacing between tones is determined by the detector characteristics. The tones are at audio frequency and the composite output may be fed directly to the voice channel input of an SSB exciter.

At the receiver the SSB equipment translates the received signal back to audio frequency. Detection circuitry at each tone frequency measures the relative phase of successive pulses and reforms the MARK-SPACE code as it appeared at the transmit terminal input.

The method used to make this phase comparison is shown in Fig. 2. Starting at rest, with no previous infor-

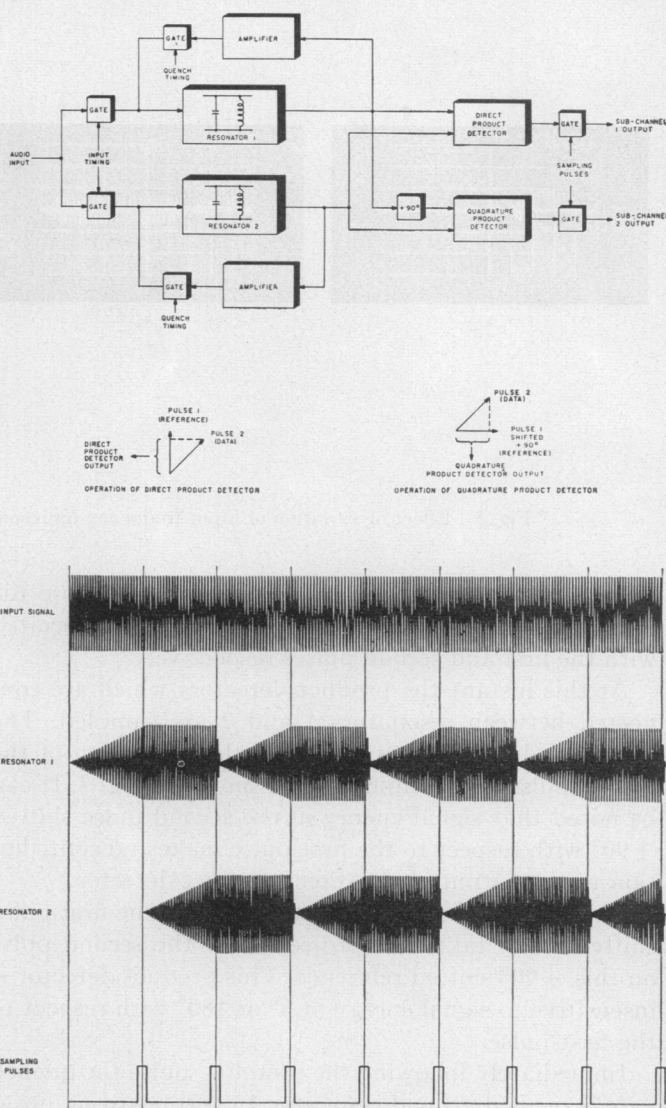


Fig. 2—Detection system.

mation in storage, the first received pulse is gated into the high Q resonant circuit, resonator 1. The circuit responds to the signal energy at the resonator frequency and at the end of the received pulse period has an amplitude proportional to the input pulse amplitude and a phase corresponding to the phase of the input signal. The input gate is then closed and the resonator used to store this amplitude and phase information.

The second pulse is admitted to resonator 2 which accumulates the amplitude and phase information associated with the second pulse. At the end of this pulse the

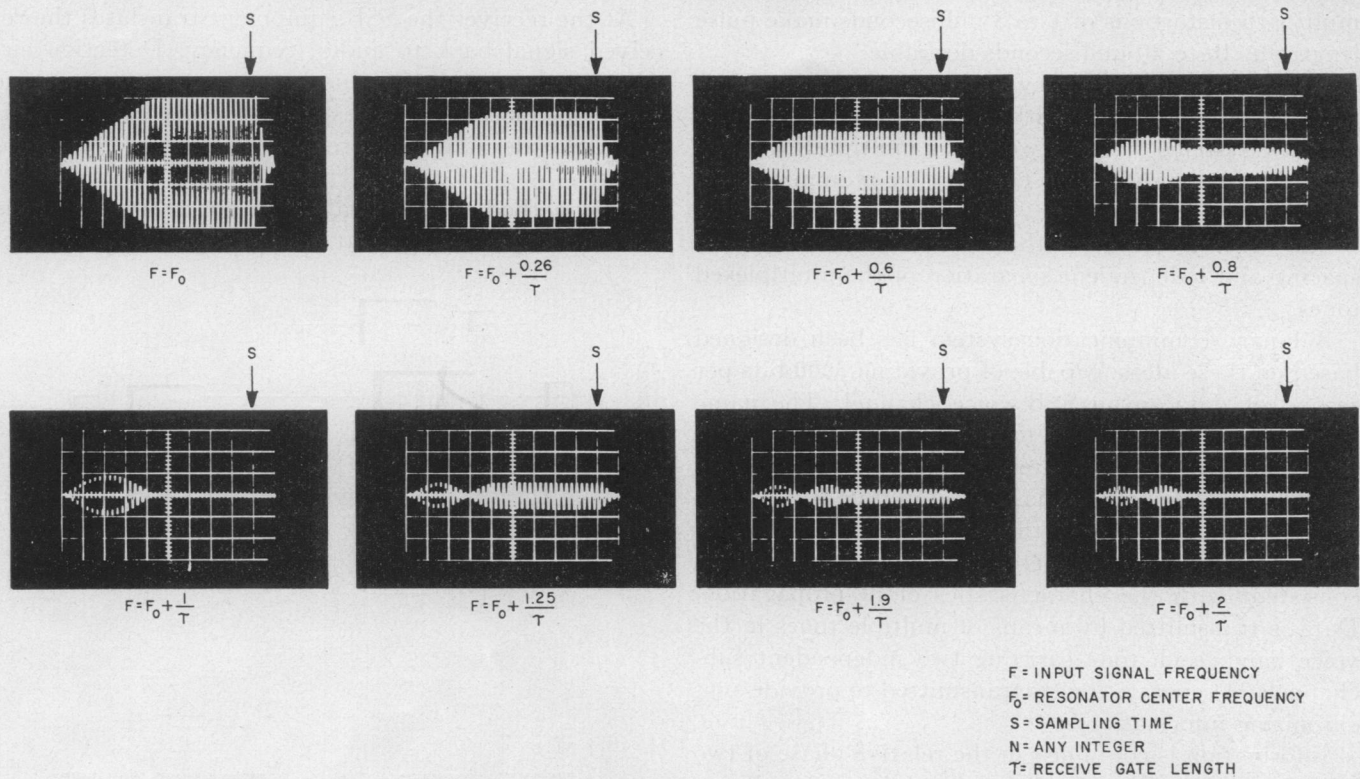


Fig. 3—Effect of variation of input frequency on resonator amplitude at sampling—orthogonal points at $f_0 + N/\gamma$.

input gate is closed. The two resonators now store the integrated amplitude and phase information associated with the first and second pulses respectively.

At this instant the product detectors which are connected between resonators 1 and 2 are sampled. The direct product detector output is the projection of the second pulse on the first pulse as shown in Fig. 2. It can be noted that signal energy in the second pulse shifted $\pm 90^\circ$ with respect to the first pulse makes no contribution to the output of the direct product detector.

The quadrature product detector, with the first pulse shifted $+90^\circ$ takes the projection of the second pulse on this $+90^\circ$ shifted reference. This product detector is insensitive to signal energy at 0° or 180° with respect to the first pulse.

Immediately following the sampling pulse the quench gate is opened around resonator 1 causing strong negative feedback to drive the stored energy to essentially zero in a time quite short compared with the transmitted pulse length. The quench gate is then closed and the input gate opened to admit the third pulse to the resonator. The comparisons between the second and third pulses are then made and resonator 2 quenched prior to admitting the fourth pulse. This procedure is continued on down the incoming pulse chain. An auxiliary circuit is used to permit the reference and data pulses alternately to be shifted 90° in the quadrature channel rather than to provide gating to switch reference pulses to one input. It should be noted that each pulse affects only two successive measurements, thus requiring phase continuity over only this period of time.

In determining the frequency spacing to be used be-

tween the multiple tones it is necessary to observe an additional characteristic of the detector. As the input frequency is varied from the center frequency of the resonator the phase change during the pulse period causes interference between the instantaneous driving signal and the signal stored in the resonator by earlier contributions. This is shown in Fig. 3. At a frequency separated from the resonator center frequency by the reciprocal of the receive gate length, τ , this interference causes the stored energy to be zero at the time the gate closes. This phenomena is repeated at frequency differences of $2/\tau$, $3/\tau$, $\dots$, etc. If additional tones are placed at frequencies corresponding to these zeros, or orthogonal points, no crosstalk results between channels. The system could then use tones spaced at frequency intervals corresponding to $1/\tau$ cycles per second (cps) with each tone carrying $2/\tau$ bits per second. Thus in a bandwidth B , $B\tau$ tones could be placed, neglecting guard bands. In time t the potential data rate of the system is then $2Bt$ bits. This corresponds to the maximum number of independent measurements in band B and time t given by Oliver, Pierce, and Shannon.²

A part of the potential data rate is used to provide tolerance for reception of signals distorted by multipath and by the unequal delays across the pass band of sideband separation filters. This is accomplished by making the receive gate-open period shorter than the length of the transmitted pulse by approximately 3 ms. This time is used for sampling and quenching the resonators as well as being available for distortion tolerance. As the tone spacing is dependent on the length of the receive gate, the tones become separated more widely than

the minimum required by the transmitted data rate.

For the 3000 bit per second system twenty tones are used, each carrying two subchannels operating at 75 bits per second per subchannel. The transmitted pulse length is 13.3 ms and the receive gate length is 10 ms. This requires a tone spacing of 100 cps, or a total bandwidth of 2000 cps. Comparing this with $2Bt$ gives an efficiency of transmission of 3000/4000 or 75 per cent.

Fig. 4 shows a comparison of error rates as a function of input signal to noise ratios for several systems. The ideal curve is computed on the basis of a perfect phase reference. The remaining curves were obtained in the laboratory using random noise sources. Various synchronous systems providing performances between those of the Kineplex and the reference fsk system could be shown; however each of these would require a detailed explanation to add useful information. As the purpose of these curves is to provide a frame of reference and show relative performance, only well known systems are used.

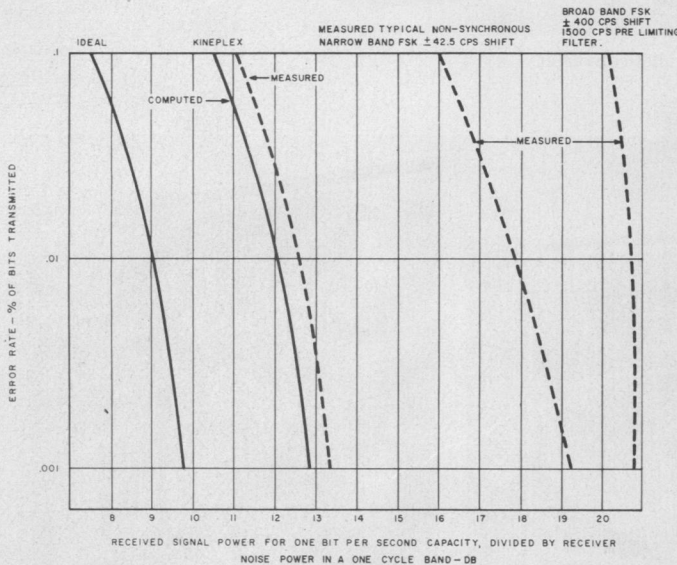


Fig. 4—Error rate vs signal-to-noise ratio for white noise.

A duplex terminal of the 3000 bit per second data system is shown in Fig. 5. Diversity operation, either frequency or space, is obtained by duplicating the detection equipment (36 inches of rack space, one side, plus power supply). The measurements of the incoming signals are made independently on the two diversity channels, which are maintained at equal gains, and the outputs of the product detectors added. Thus the diversity decision is based on the decision obtained with the stronger of the two signals.

The transmit equipment accepts synchronous data on 40 parallel inputs, each operating at 75 (or optionally 45 or 56) bits per second and provides a multitone output which may be fed directly into the voice frequency input of an SSB exciter or into a telephone channel for remote operation. The receive terminal equipment accepts the audio outputs of two diversity receivers, independently detects and diversity combines these signals, and provides 40 parallel regenerated outputs corre-

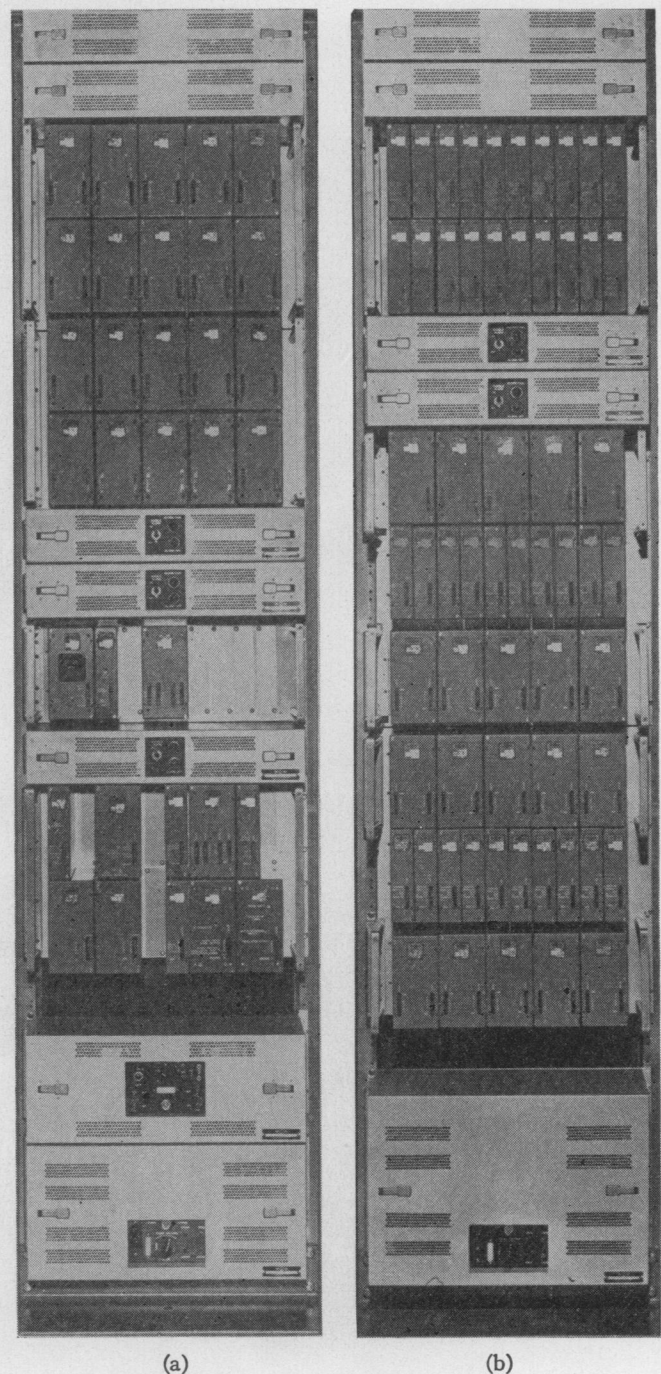


Fig. 5—3000-bit data system. (a) Front. (b) Rear.

sponding to the transmitted information.

Converters to equip the data system for use in teleprinter service occupy one side of an additional rack. These provide for 40 channels operating at 100 wpm (or optionally 60 or 75 wpm), accepting nonsynchronous start-stop inputs from keyboards or tape and providing 60-ma neutral outputs for operation of page printers. Other converters may be used to provide for a variety of services. Shift registers to convert between high speed time sequential data at speeds to 3000 bits per second and the data link are shown in Fig. 6.

All units are of modular design and are completely transistorized. Light components are mounted on printed circuit boards with heavy components sup-



Fig. 6—Series/parallel converter.

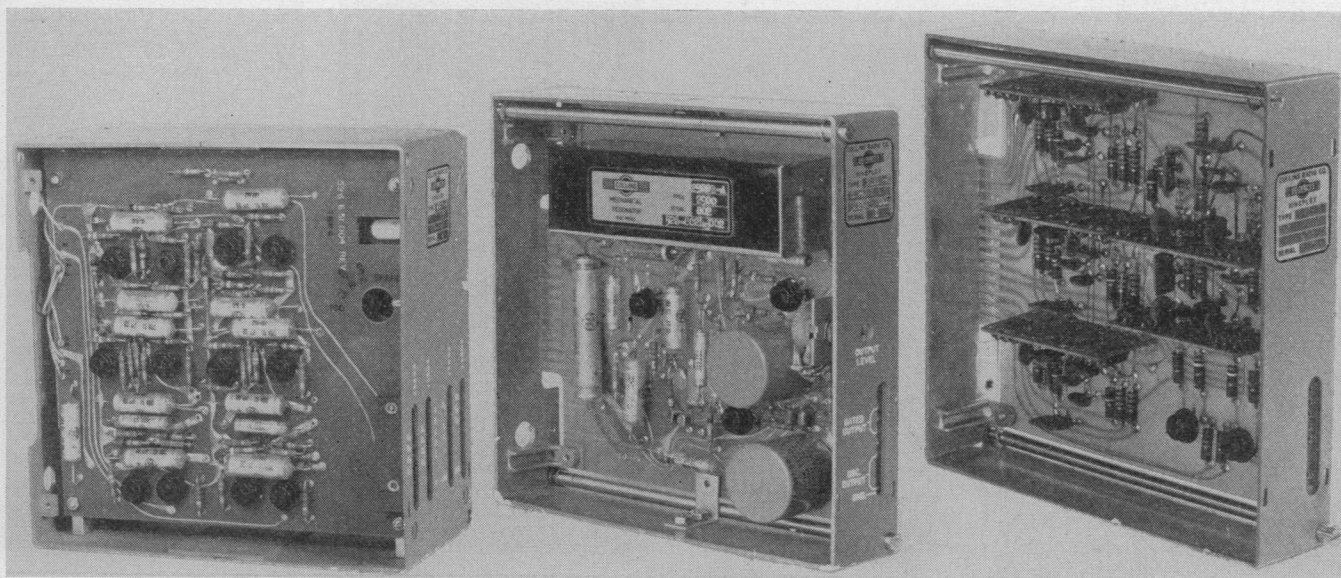


Fig. 7—Typical modules.

ported on shelves in the module. The equipment is designed for operation from dc power at 21 to 31 volts and is shown with power supplies which derive this power from 115-volt 60-cps service. Typical modules are shown in Fig. 7.

A high frequency SSB circuit has been set up between Cedar Rapids, Iowa and Canoga Park, California, to make propagation measurements and to test the operation of the system. Additional propagation measurements of the phase stability of signals received from WWV have been made. Fixed frequency SSB receivers are used for both series of measurements. All injection

voltages are derived from a stabilized master oscillator which is locked to a frequency standard. The receiving installation is shown in Fig. 8.

Some of the results of the WWV phase stability measurements, over the Washington, D. C., to Canoga Park, California, path, are shown in Fig. 9.⁵ These photographs show the relative phase and amplitude of successive pairs of pulses 22 milliseconds in length. Detectors of the type described above were used to receive WWV.

⁵ A report describing these tests in detail is being prepared by G. Barry, Collins Radio Company.



Fig. 8—HF receive terminal.

The WWV carrier transmission may be thought of as a long series of 22 millisecond pulses with successive pulses in phase, providing a maximum output on the direct product detector (Fig. 2) and a zero output on the quadrature product detector. The direct product detector output was connected to the vertical plates of an oscilloscope, and the quadrature product detector output was connected to the horizontal plates. Equal gains were used on the two axes. Z-axis (intensity) modulation was used to turn on the beam only at the sampling time. The number of samples per photograph was then varied by changing exposure time.

The first photograph shows the response of the detector to a signal derived from a local frequency standard. This is of constant amplitude and shows no phase difference between pulses. The second photograph shows the response to amplified receiver noise indicating an essentially random distribution of amplitude and phase. Typical samples of received data are shown in the remaining photographs.

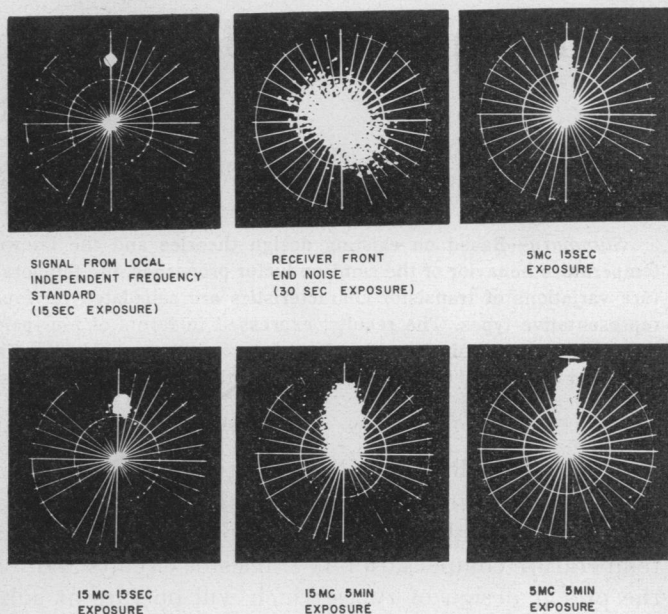


Fig. 9—Polar display of incremental phase shift.

Especially important is the shape of the pattern of samples. Additive noise would cause the X-axis deflection to be independent of signal amplitude on the Y axis and result in an essentially rectangular pattern. Phase shift in the propagation path due to rapid path length changes, etc., would result in phase shifts which would tend to be independent of signal amplitude. This would cause the pattern to lie along lines of constant phase shift in a pie-shaped segment.

As may be seen, the test patterns are narrow and nearly rectangular, indicating good relative phase stability between adjacent pulses.

Test transmissions of the data system have been carried out over the path between Cedar Rapids, Iowa, and Canoga Park, California. The received audio frequency signals are transmitted over approximately 30 miles of class C telephone circuit to the Burbank laboratory before detection. Tests to date have used teleprinter data to provide input and output signals. Twelve channels operating on six adjacent tones have been used for test and evaluation purposes. Forty channel circuit loading has been tested using four data channels plus 18 additional unkeyed tones. Preliminary results have been favorable and confirm conclusions based on system characteristics and propagation measurements.

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