April 6, 1948. W. M. GOODALL 2,438,908

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed May 10, 1945 11 Sheets-Sheet 1

FIG. 1

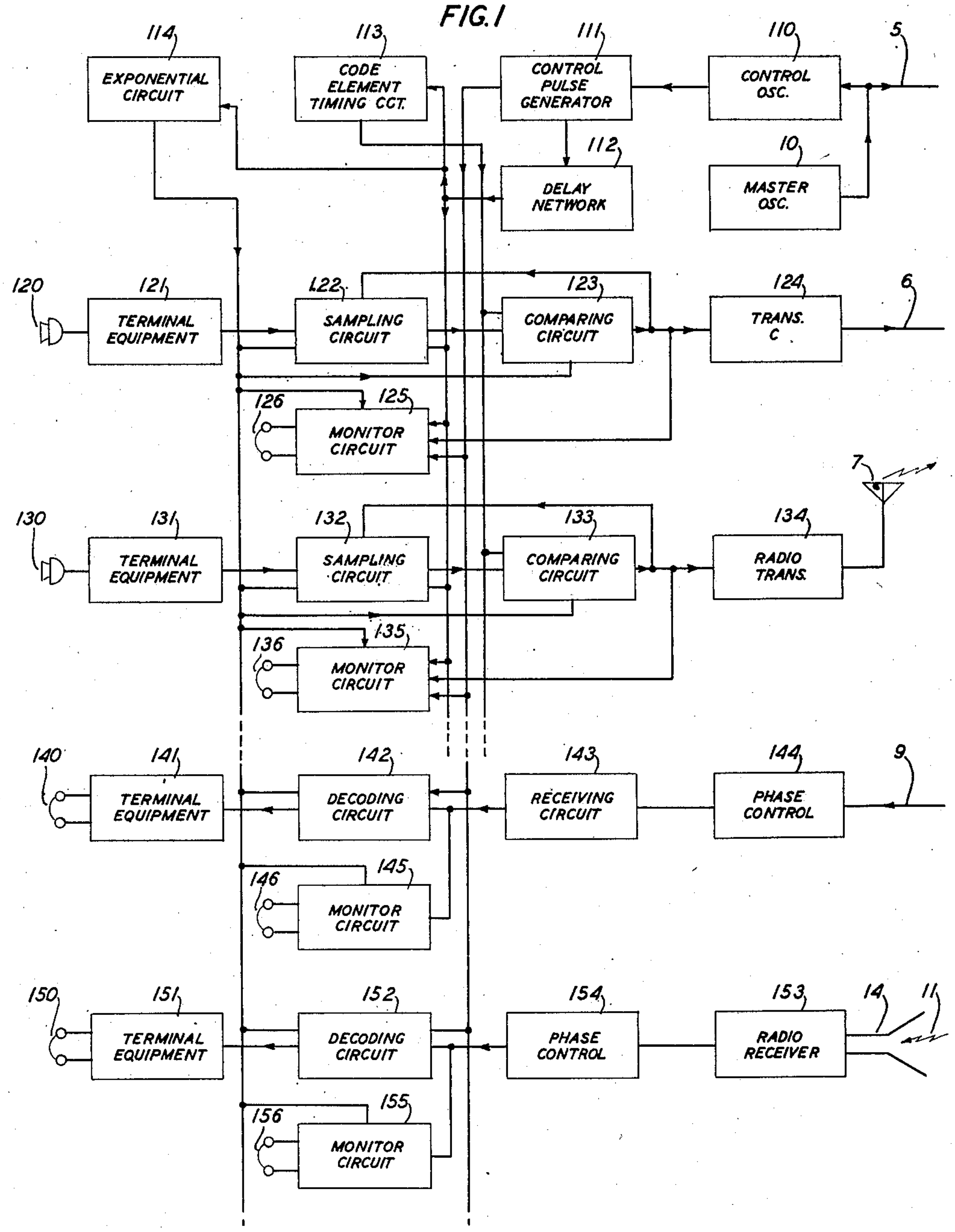


FIG. 12

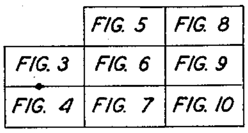
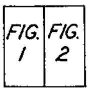
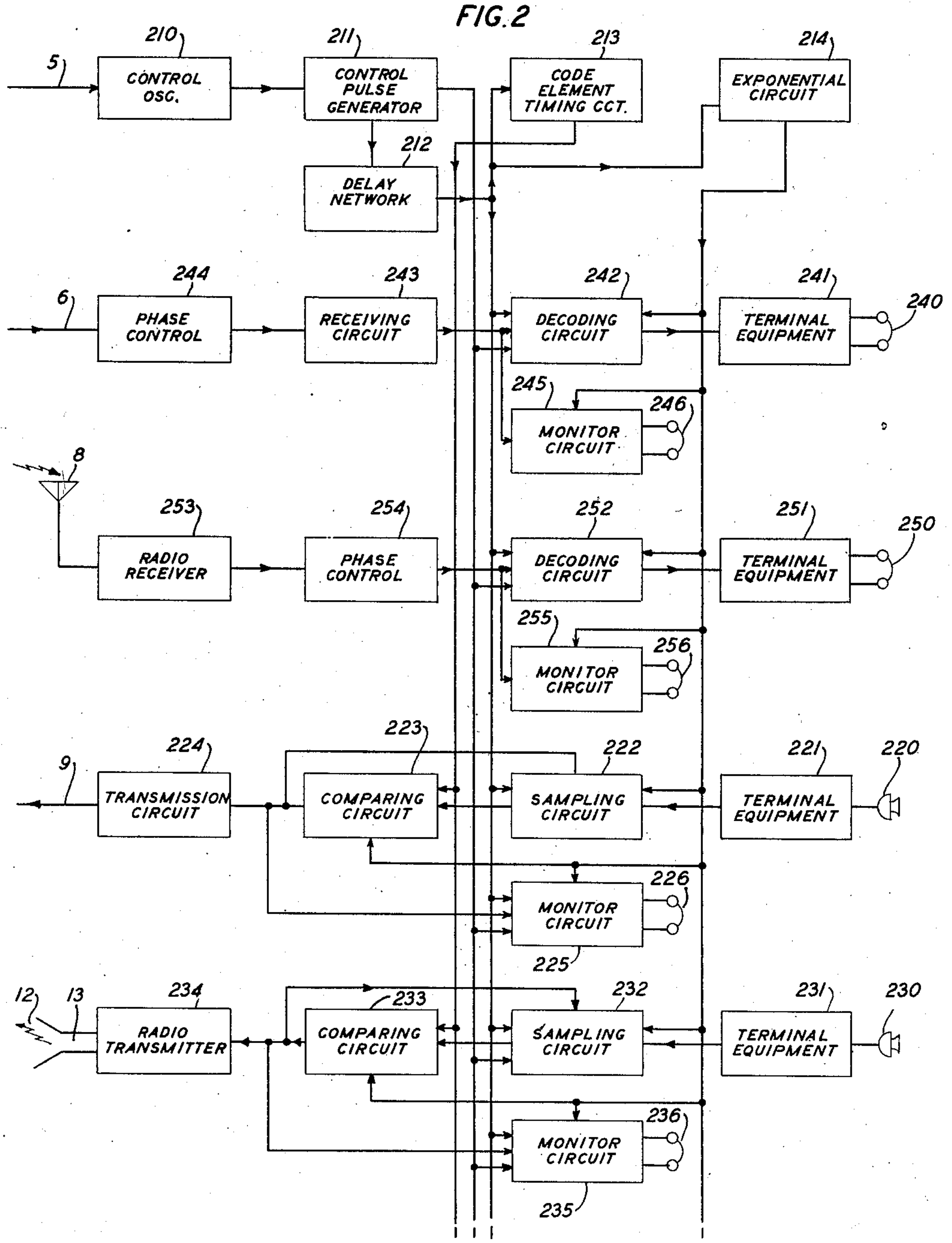


FIG. 11



INVENTOR
W. M. GOODALL
BY William F. Simpson.
ATTORNEY

FIG. 2



INVENTOR
W. M. GOODALL
BY William F. Simpson.
ATTORNEY

April 6, 1948. W. M. GOODALL 2,438,908

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed May 10, 1945 11 Sheets-Sheet 3

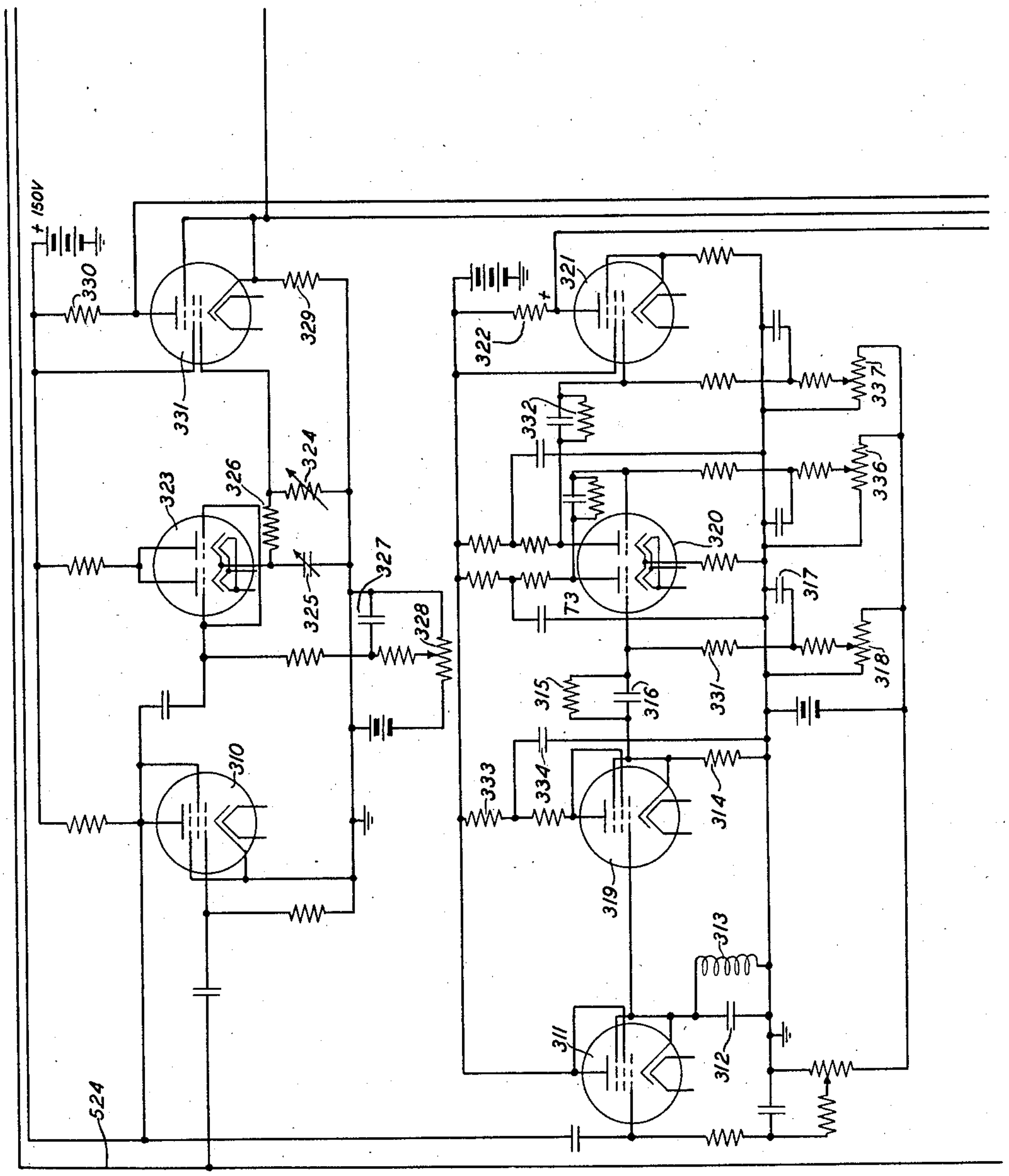


FIG. 3

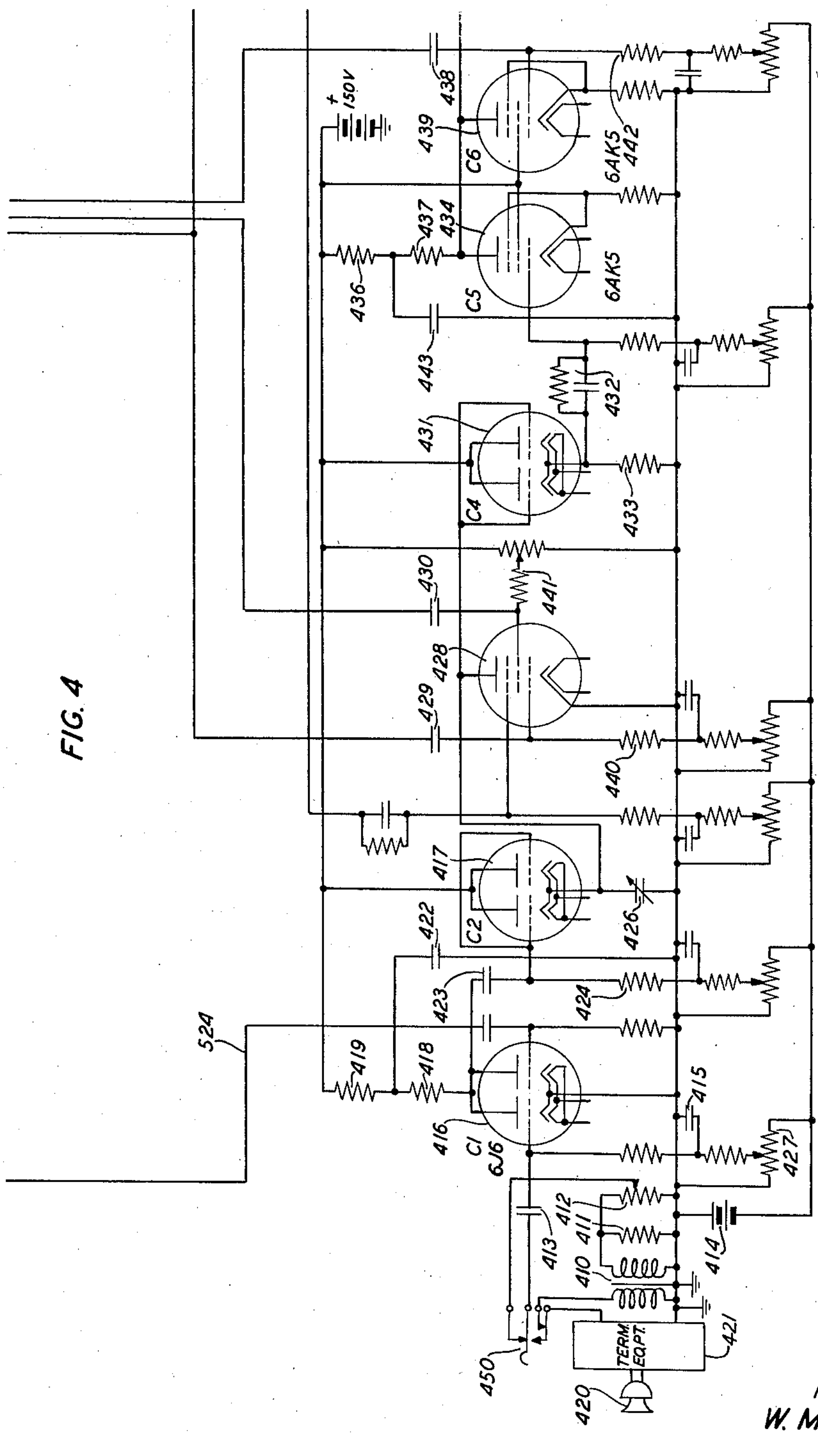
INVENTOR
W. M. GOODALL
BY William F. Simpson
ATTORNEY

April 6, 1948. W. M. GOODALL 2,438,908

PULSE CODE MODULATION COMMUNICATION SYSTEM

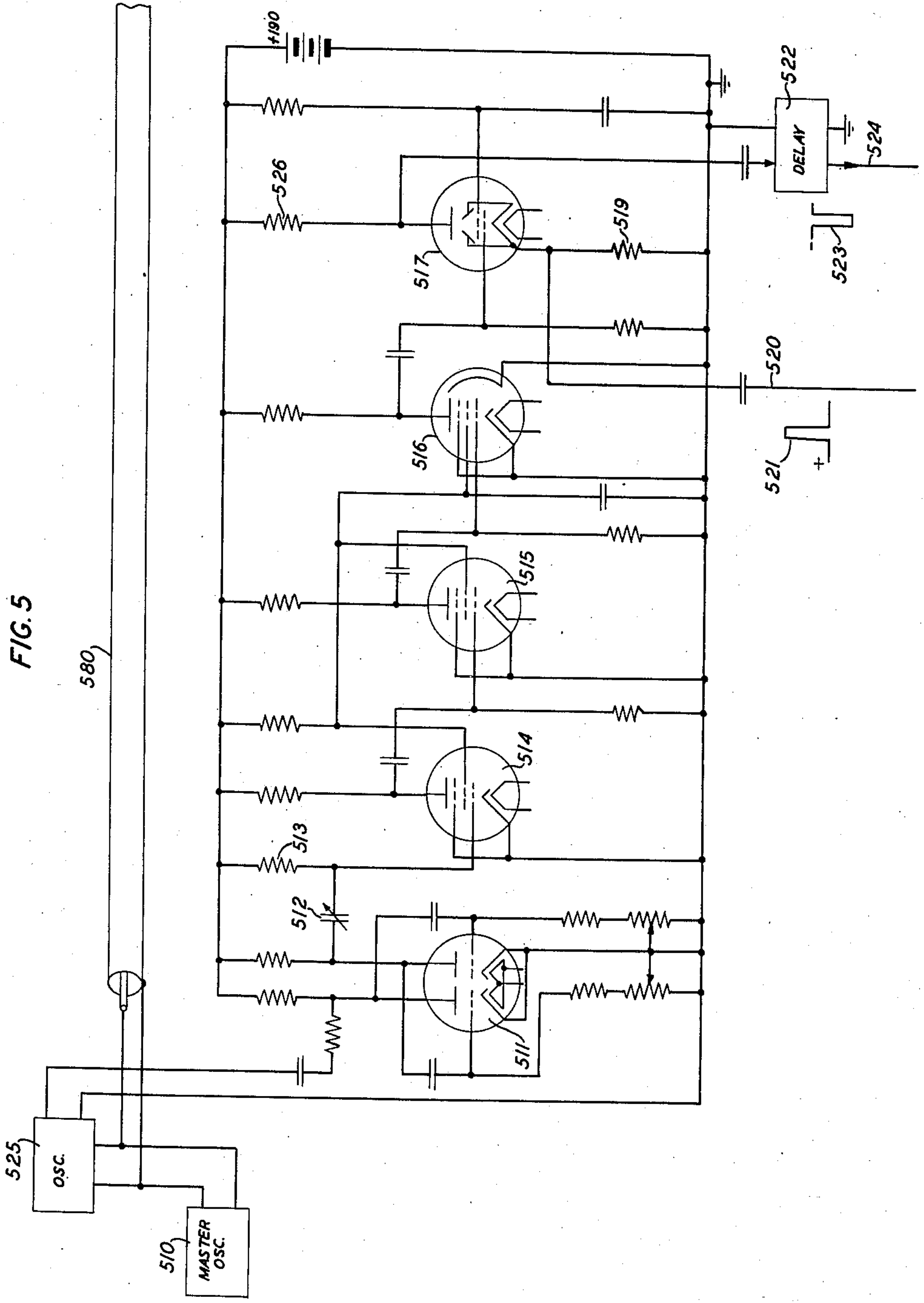
Filed May 10, 1945 11 Sheets-Sheet 4

FIG. 4



INVENTOR
W. M. GOODALL
BY William F. Simpson.
ATTORNEY

FIG. 5



INVENTOR
W. M. GOODALL
BY William F. Simpson.
ATTORNEY

April 6, 1948. **W. M. GOODALL** **2,438,908**

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed May 10, 1945 11 Sheets-Sheet 6

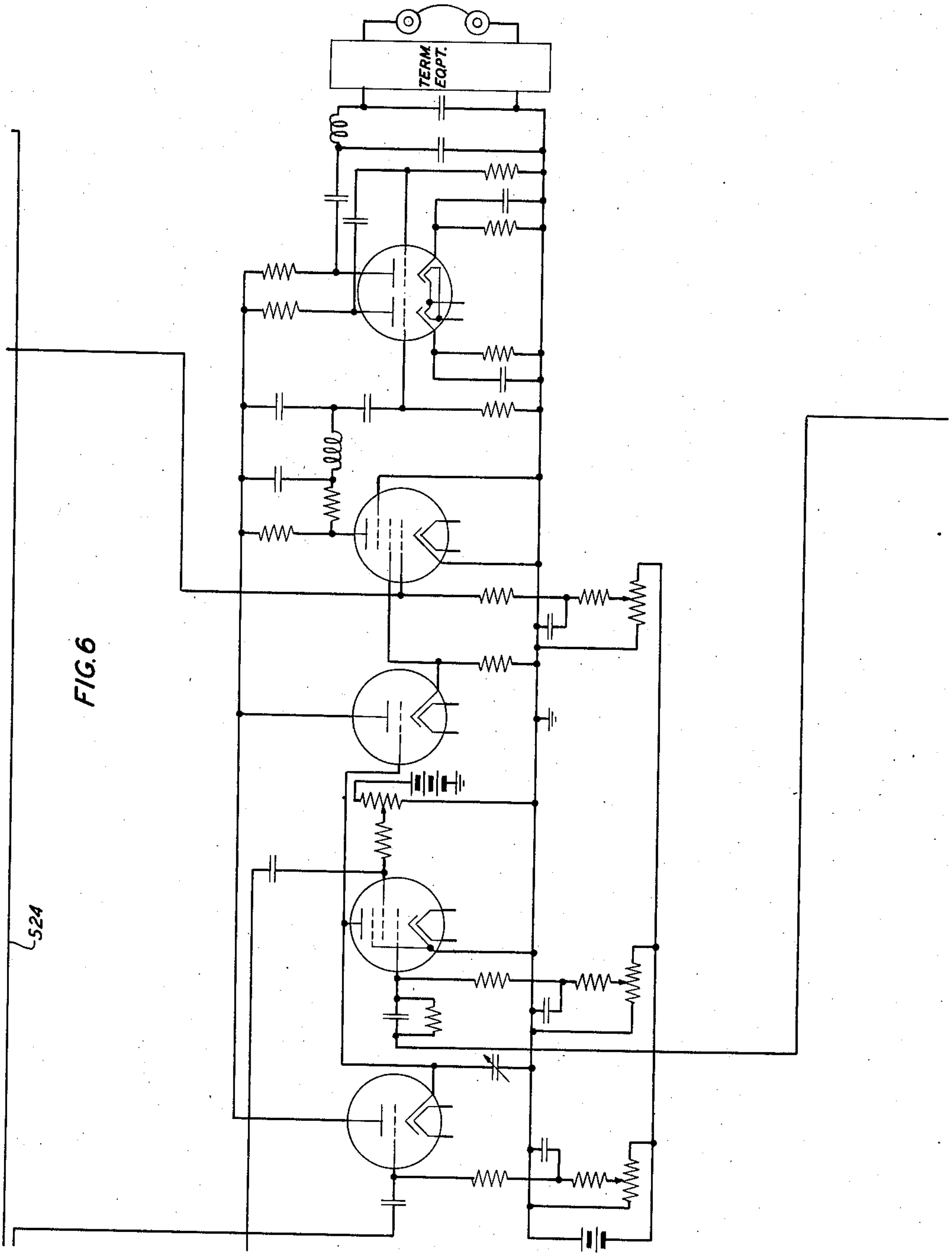


FIG. 6

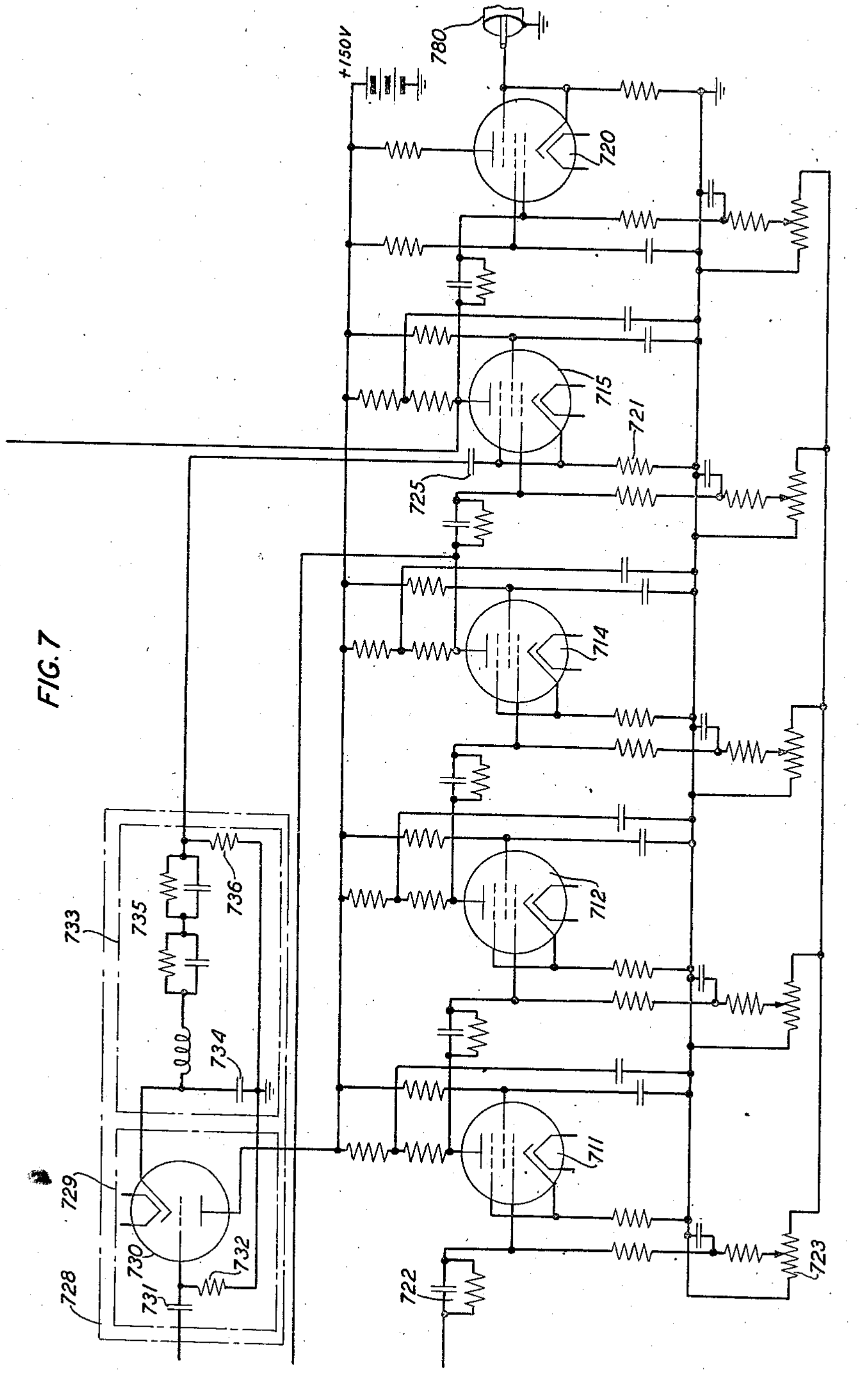
INVENTOR
W. M. GOODALL
BY William F. Simpson.
ATTORNEY

April 6, 1948. W. M. GOODALL 2,438,908

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed May 10, 1945 11 Sheets-Sheet 7

FIG. 7



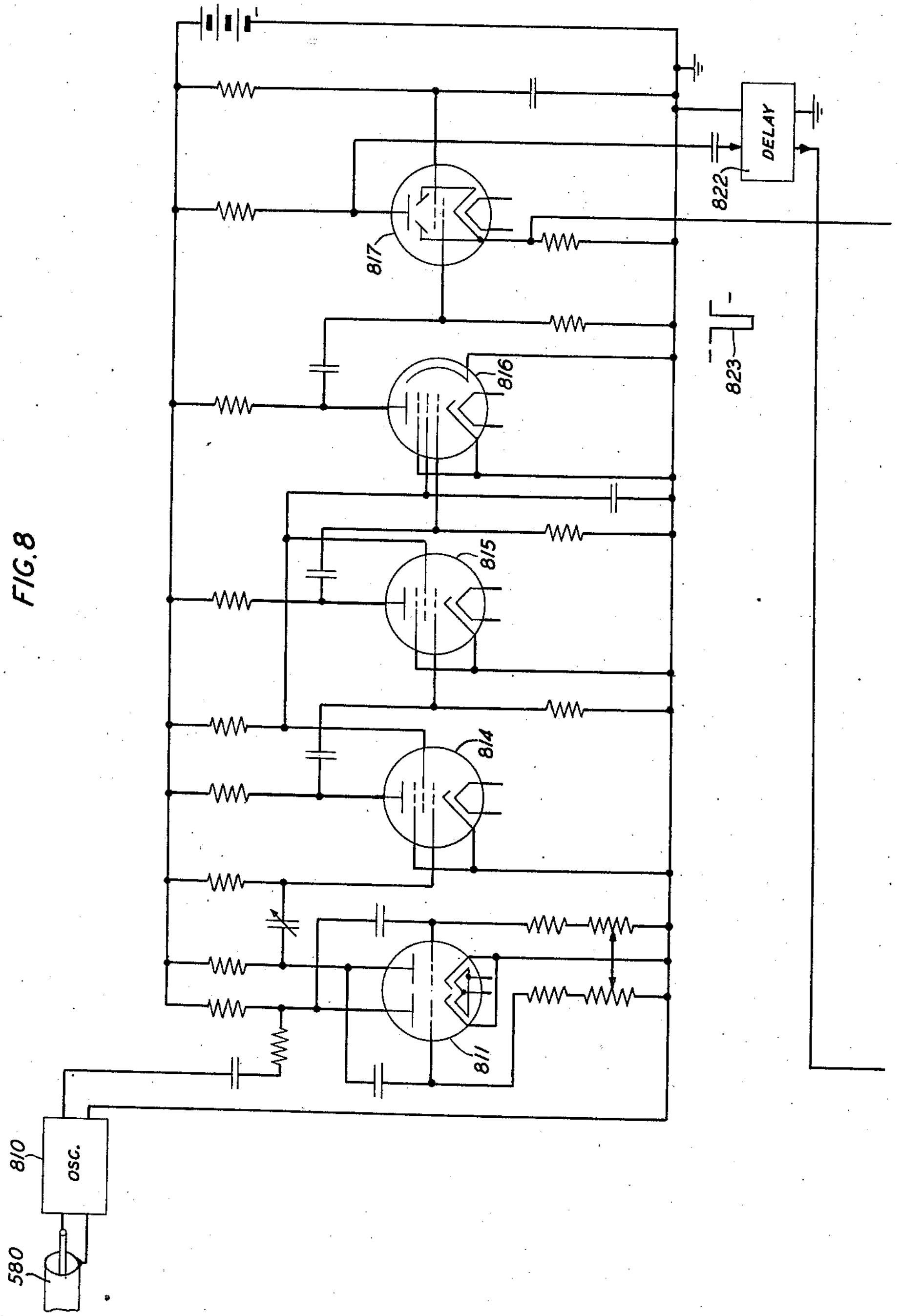
INVENTOR
W. M. GOODALL
BY William F. Simpson.
ATTORNEY

April 6, 1948. W. M. GOODALL 2,438,908

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed May 10, 1945 11 Sheets-Sheet 8

FIG. 8



INVENTOR
W. M. GOODALL
BY William F. Simpson.
ATTORNEY

April 6, 1948.　　W. M. GOODALL　　2,438,908

PULSE CODE MODULATION COMMUNICATION SYSTEM

Filed May 10, 1945　　11 Sheets-Sheet 9

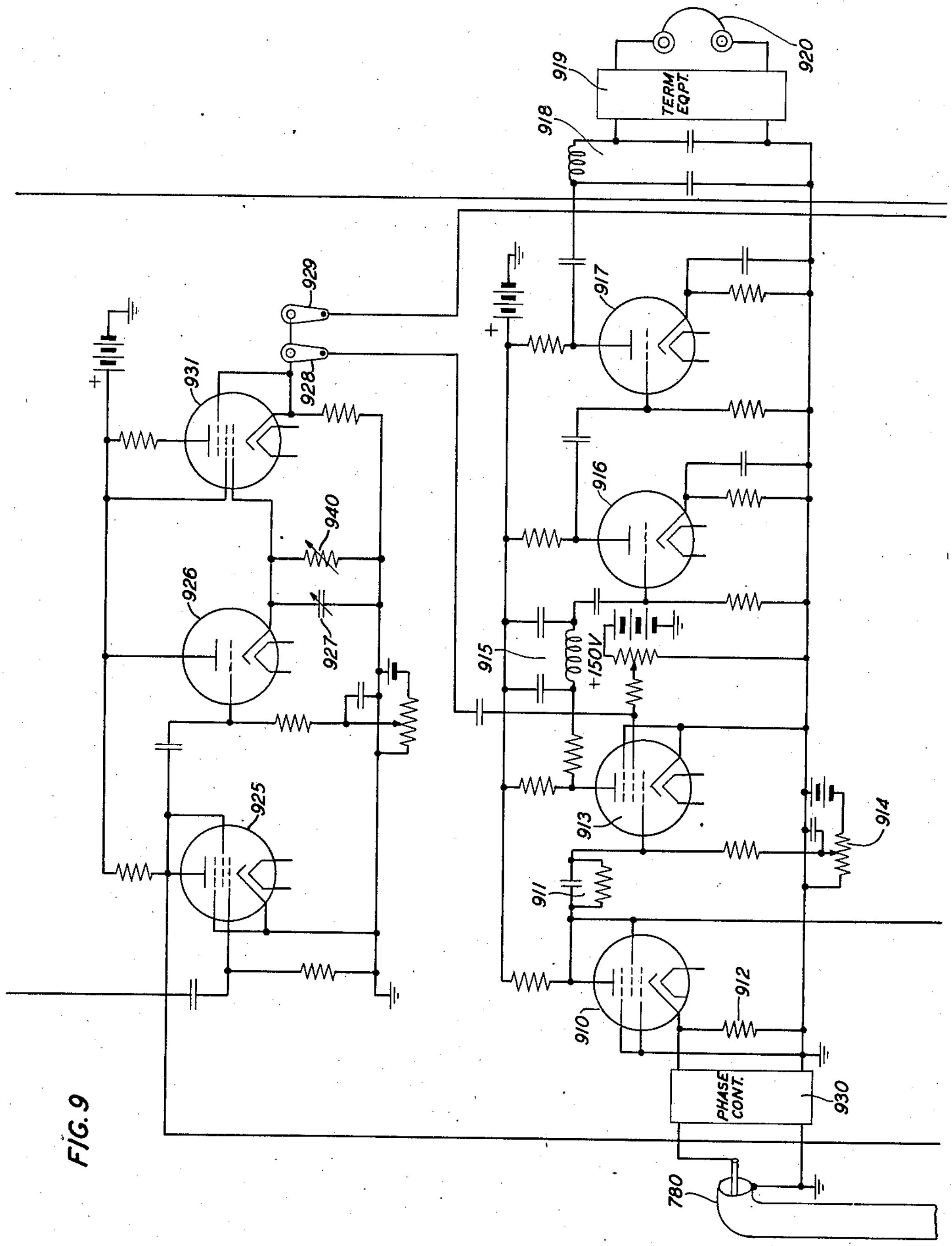


FIG. 9

INVENTOR
W. M. GOODALL
BY William F. Simpson.

ATTORNEY

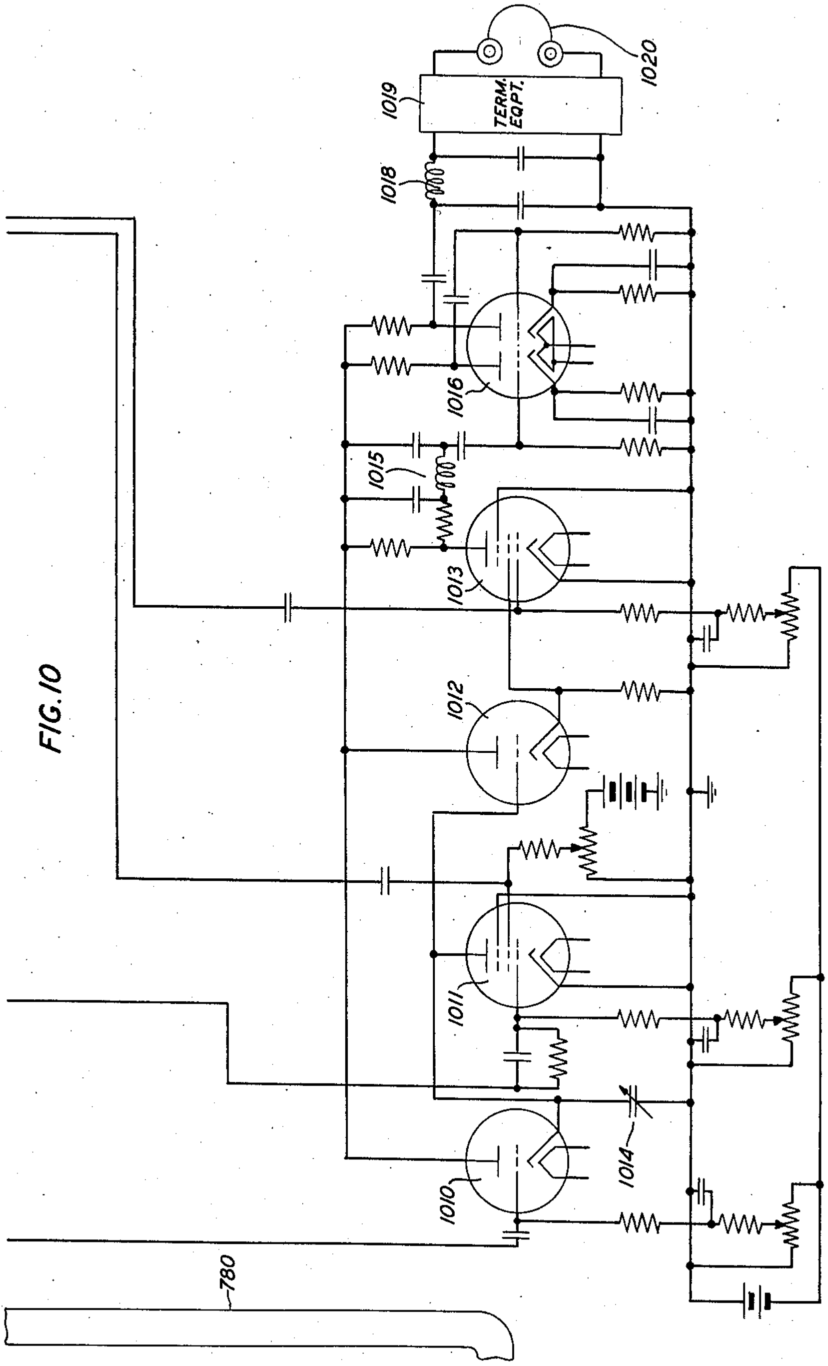


FIG. 10

INVENTOR
W. M. GOODALL
BY William F. Simpson
ATTORNEY

FIG. 13

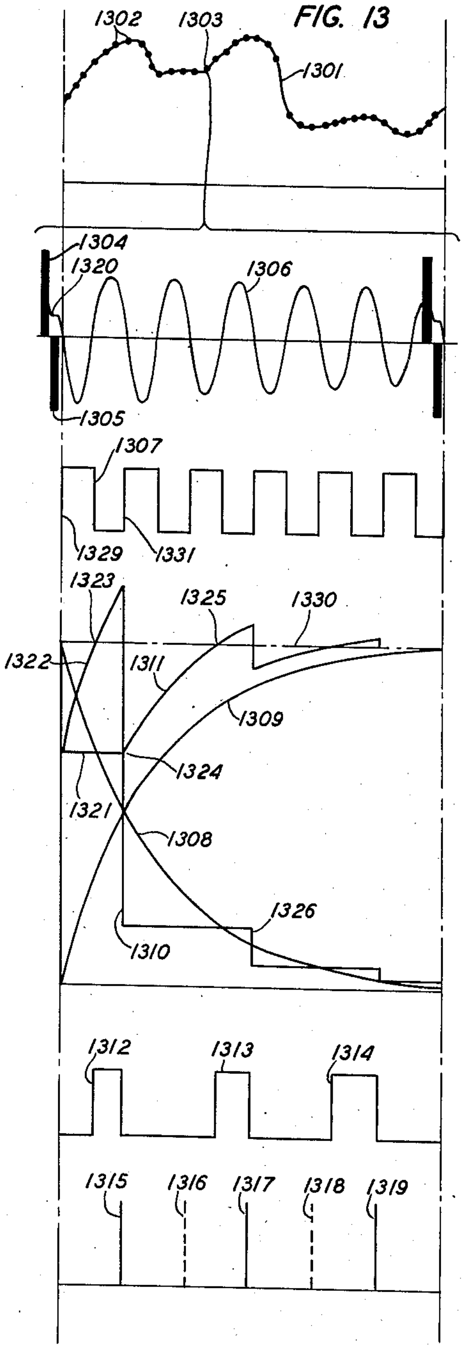
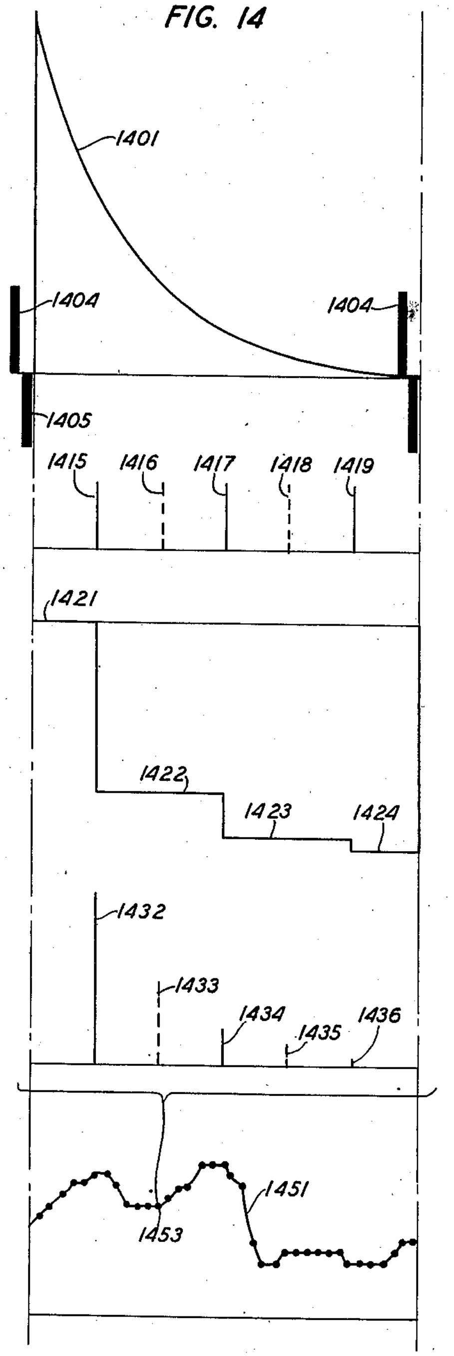


FIG. 14



INVENTOR
W. M. GOODALL
BY William F. Simpson
ATTORNEY

Patented Apr. 6, 1948 **2,438,908**

UNITED STATES PATENT OFFICE

2,438,908

PULSE CODE MODULATION COMMUNICATION SYSTEM

William M. Goodall, Oakhurst, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application May 10, 1945, Serial No. 592,958

13 Claims. (Cl. 179—1.5)

1

This invention relates to communication systems for the transmission of complex wave forms of the type encountered in speech, music, sound, mechanical vibrations and picture transmission by means of code groups of a uniform number of signaling impulses, each of which comprises any one of a plurality of different signaling conditions or types of signaling conditions transmitted in succession.

This invention is an improvement upon a similar system described in my patent copending application Serial No. 554,495, filed September 16, 1944.

The object of the present invention is to provide an improved and simplified apparatus and method of generating a plurality of series of permutation code groups of pulses representing a complex wave for transmission over an electrical transmission path in order to secure a greater signal-to-noise ratio for the reconstructed signal wave at the receiving station. In other words, the information transmitted by permutation code pulses may be transmitted over a very noisy transmission system without adding appreciable amounts of noise to the received signal.

Another object of this invention is to provide methods and systems for the rapid representation of the instantaneous amplitudes of the complex waves by permutation code groups of pulses in an improved and simplified manner.

A feature of this invention relates to coding and decoding equipment which employs a continuously varying exponential wave both for coding pulses at the transmitting end and decoding pulses at the receiving end, instead of a step wave form as employed in the above-identified application.

Another feature of this invention relates to methods of operation and equipment for controlling the character of the pulses of each of the permutation code groups of pulses in accordance with the instantaneous amplitude of a complex wave by means of a single electron conduction device which in the exemplary embodiment set forth herein is exemplified by a multielement vacuum tube frequently called a pentode tube.

Another object of the present invention is to provide receiving equipment which employs a continuously varying exponential wave for decoding permutation code groups of pulses and reconstructing a complex wave therefrom.

Another feature of this invention relates to equipment for controlling the length of pulses transmitted so they will be suitable for controlling radio or other high frequency transmitters, including transmitting equipment capable of transmitting the highest radio frequencies.

2

Another object of the present invention is to provide apparatus for modifying the input of complex waves in such a way that they will be more suitable for controlling pulse generating equipment in accordance with the present invention so that a larger portion of the available amplitude range of the complex wave form is employed and at the same time permitting a larger amplitude range of complex wave forms to be employed without overloading the coding equipment.

Another feature of this invention relates to the use of an instantaneous amplitude compressing device for compressing the instantaneous amplitudes of the complex wave forms applied to the coding equipment prior to the transmission of these complex waves.

Another feature of the invention relates to receiving equipment for reconstructing complex wave forms represented by permutation code pulses in which the permutation code pulses represent a compressed wave form at the transmitting station without the use of any expanding equipment at the receiving station to compensate for the distortions of the compressing equipment at the transmitting station. Applicant has discovered that many of the advantages of compression can be obtained by compressing the wave before it is applied to the sampling and coding equipment and then a complex wave regenerated in suitable form at the receiving station from the received code signals without the use of corresponding expansion equipment and without objectionable distortion which is usually manifest by undesirable added frequency components when signaling waves are instantaneously compressed.

Briefly, in accordance with the present invention equipment is provided for generating synchronizing or control pulses from which a plurality or group of timing pulses are generated. The synchronizing or control pulses are employed to control the generation of a continuously varying exponential wave and also to control the sampling of the instantaneous amplitude of the complex wave form which it is desired to transmit to a distant station. Prior to this sampling the complex wave is compressed by means of one or more non-linear circuit elements. The compression of the wave prior to its being sampled provides a two-fold advantage. First on weak signals it causes the range of instantaneous amplitudes applied to the coding to vary through greater amplitude and second when strong signals are applied it tends to prevent the strong signals from overloading the coding equipment.

The magnitude of the samples of the compressed wave together with the continuously varying exponential wave and the output signals are applied to a coding tube which tube combines the values enumerated above and applies them to a comparing circuit which compares the output of the above-mentioned coding tube with a continuously varying exponential wave for determining the character of each of the signaling pulses transmitted over this system. At the receiving station the received pulses, together with a similar exponential wave is applied to other tubes for causing the reconstruction of the complex wave.

Other means is provided for sampling or deriving an electrical quantity which is a function of the amplitude of the complex wave after said complex wave has been compressed. The magnitude of the electrical quantity or sample is then compared with the magnitude of the continuously varying exponential wave and if the sum of these two waves exceeds a predetermined value pulses of a predetermined kind or character are transmitted. During or after the transmission of the pulses in question the magnitude of the sample is reduced by an amount equal to the portion magnitude of the sample represented by the pulse transmitted. Thereafter the remaining portion of the sample is again compared with the continuously varying exponential wave and the above action repeated until all of the pulses in a given permutation code group or series has been transmitted, at which time another sample is obtained, which in turn is similarly compared with another continuously varying exponential wave similar to the first exponential wave described above, so that a succeeding series of pulses is likewise generated and transmitted. The amount subtracted from the electrical quantity due to the transmission of the various pulses is the total maximum possible value multiplied by

$$\frac{1}{A^n}$$

where A is a constant greater than 1 and usually 2 and n is the ordinal or digital number of the pulse transmitted.

At the receiving station a control pulse generator, and a continuously varying exponential wave generator are provided which are similar to the respective circuits at the transmitting station. In addition, decoding equipment is provided in which the received pulses are employed to synthesize and reconstruct a complex wave having a wave form similar to the wave form of the complex wave sampled at the receiving station.

Novel features of this invention which are believed to be characteristic thereof are set forth with particularity in the claims appended thereto.

The invention itself, however, both as to its organization and method of operation, together with other objects and features thereof, may be best understood from the following description of an exemplary system embodying the invention when said description is read with reference to the accompanying drawings, in which:

Figs. 1 and 2 show in diagrammatic form the various elements of an exemplary system embodying the present invention and the manner in which the various elements cooperate one with another;

Figs. 3 to 10 when positioned adjacent one another as shown in Fig. 12 show in detail the various circuits and equipment of an exemplary communication system embodying the present invention; Figs. 3 and 5 may be common to all the channels at a transmitting terminal and Fig. 8 and the upper portion of Fig. 9 may be common to all the channels at a receiving terminal; in case of two-way communication these figures may be common both to all of the transmitting channels and to all of the receiving channels at the respective stations;

Fig. 11 shows the manner in which Figs. 1 and 2 are positioned adjacent one another;

Fig. 12 shows the manner in which Figs. 3 to 10, inclusive, are positioned adjacent one another; and

Figs. 13 and 14 show graphs of the various current or potential wave forms at various places in the system.

Figs. 1 and 2 when arranged as shown in Fig. 11 show in diagrammatic form the various circuit elements and apparatus and the manner in which they cooperate one with another to form an exemplary system embodying the present invention. Fig. 1 shows the apparatus and circuits at one station while Fig. 2 shows similar apparatus and circuits at a second station. As shown in Figs. 1 and 2, two transmission paths or channels are provided between the two stations in each direction. The transmission paths as well as the other interconnections between the various elements which cooperate to form the exemplary system described herein are shown as single lines in Figs. 1 and 2. Persons skilled in the art will readily understand that the single lines interconnecting the different elements in Figs. 1 and 2 represent the desired or necessary number of conductors which extend between the respective elements of the system. It will be obvious to persons skilled in the art that additional channels in either or both directions may be provided between each of these stations. It will also be obvious to persons skilled in the art that additional stations or terminals may be provided and similar transmission paths or channels extended between any or all of the various stations or terminals.

Furthermore, the signals transmitted from either of the stations of Fig. 1 or 2 may be received by other receiving devices and systems, as for example, by the system disclosed in my copending application Serial No. 554,495. Likewise the receiving apparatus of Fig. 1 or 2 may receive signals from other types of transmitting systems, as for example, from the transmitting stations shown in my above-identified copending application which is incorporated herein as if fully set forth herein.

As shown in Figs. 1 and 2, lines 6 and 9 represent two communication paths between the two stations. Signals are transmitted over line 6 from the station shown in Fig. 1 to the station shown in Fig. 2. Signals are transmitted over line 9 from the station shown in Fig. 2 to the station shown in Fig. 1. These lines 6 and 9 represent communication paths between the two stations which may be of any suitable type for the transmission or conveyance of electrical signaling impulses of proper frequency range. These paths may be used independently of each other or in pairs to provide two-way communication circuits. These paths are illustrated in Figs. 1 and 2 by a single line and persons skilled in the art will readily understand that these lines represent any and all types of communication paths and combinations thereof including open wire lines, cable conductors, testing pairs, channels of carrier current systems, coaxial lines and cables, wave guides, radio channels and may also include time division multiplex channels. Furthermore, these transmission paths may include suitable amplifiers, filters, predistortion networks, equalizing networks, gain control networks and circuits, phase control circuits and networks, repeaters, repeater stations, as well as signal operated switching apparatus as well as other signal operated devices which control the direction of transmission. In addition, when the transmission path is over or includes a coaxial cable, the transmission system may include any or all of the features disclosed in or referred to in United States Patents 2,343,568, granted to L. W. Morrison, Jr., on March 7, 1944; 2,212,240, granted August 20, 1940, to Lalande et al.; and 2,095,360, granted October 12, 1937, to Green. These features may also be employed for other types of conductors when desired. Any or all of the transmission channels between any or all of the stations may also include regenerative repeaters as well as other equipment associated with each of the respective types of transmission paths suitable for terminating and interconnecting the various types of transmission lines so that they will each cooperate with the adjacent sections to form a continuous transmission channel between the two stations. In addition to lines **6** and **9**, two radio channels are shown in Figs. 1 and 2. Transmitting antenna **7** and receiving antenna **8** represent one of the radio channels while wave guide **13** and horn or radiator **12** and horn **11** and wave guide **14** illustrate a second radio channel between these stations. A typical example of a radio channel including radio relay repeater stations suitable for the transmission of pulses of the type employed in the exemplary system described herein is described in detail in a series of papers published in the Proceedings of the Institute of Radio Engineers for November 1934, entitled "An experimental television system," part 1 of which is entitled "Introduction," which is by E. W. Engstrom, part 2 of which is entitled "The transmitters," and is by Kell, Bedford and Trainer, part 3 of which is entitled "The receivers," and is by Holmes, Carlson and Tolson, and part 4 of which is entitled "The radio relay link for television signals," and is by Young. Another suitable type of radio amplifier, repeater and transmitter is described in detail in an article entitled "High gain amplifier for 150 megacycles" by Rodwin and Klenk, published in the Proceedings of the Institute of Radio Engineers for June 1940. Typical wave guide and horn or radiator structures are described in United States Patent 2,206,923, granted to Southworth July 9, 1940. The foregoing publications and patents are hereby made a part of the present application to the same extent as though set forth herein in full.

In addition, a synchronizing path or channel **5** is shown extending between the two stations shown in Figs. 1 and 2. This control path or channel may be similar to other transmission paths between the stations. Furthermore, if it is so desired, the synchronizing signals or the control frequency may be transmitted over one or more of the other transmission paths extending between the stations. Inasmuch as there are numerous types of synchronizing apparatus in the prior art which will operate over the same transmission paths as employed for the transmission of communication systems and since the operation of this type of equipment is well known and understood by persons skilled in the art, it is considered unnecessary to further expand the present disclosure to show details of a typical system of this type. It is understood, of course, that such equipment as will cooperate with the various circuits of the present invention may be provided when it is so desired.

Each of the stations is provided with certain control equipment which may be common to all the circuits terminating at that station or which may be common to a plurality of the circuits terminating thereat. Of course, this common equipment may be provided for each of the individual circuits, if so desired, as is well understood by persons skilled in the art. However, in the system shown in Figs. 1 and 2, control circuits and equipment common to all the channels shown terminating at each of the respective stations are shown at the top of each of these figures.

The common equipment at station **1** comprises a control oscillator **110** which may be of any suitable type as, for example, the type described in detail in one or more of the following patents: 1,476,721, Martin, December 11, 1923; 1,660,389, Matte, February 28, 1928; 1,684,455, Nyquist, September 18, 1928; and 1,740,491, Affel, December 24, 1929, the disclosures of which are hereby made a part of the present application as if fully included herein.

The output of the control oscillator is coupled to control a control pulse generator **111**. The output of this generator extends to receiving and monitoring equipment as shown in the drawing and also to delay network **112**. The delay network **112** may be of any suitable type of delay network as, for example, one or more sections of one or more of the types disclosed in United States Patent 1,770,422, granted July 15, 1930, to Nyquist. The output of the delay network **112** extends to sampling circuits **122** and **132** and also to a code element timing circuit **113**. The output of the code element timing circuit extends to the coding and comparing circuits **123** and **133**. The output of the delay network **112** also extends to the exponential circuit **114**. Similar common equipment comprising a control oscillator **210**, control pulse generator **211**, delay network **212**, code element timing circuit **213** and exponential circuit **214** is provided at the station shown in Fig. 2.

In addition to the control oscillators **110** and **210** at each of the control stations, a master oscillator **10** is shown in Fig. 1. This master oscillator may be located at either of the stations and may replace the control oscillator **210** or **110** at either of these stations. However, the master oscillator is frequently located at some central point and provides a control frequency for an entire nation-wide system or for some smaller portion or sections of a large system. Typical oscillators for standard frequency systems suitable for use as the master oscillator and also for the control oscillators are disclosed in United States Patents 1,788,533, Marrison, January 13, 1931; 1,931,873; Marrison, October 24, 1933; 2,087,326, Marrison, July 10, 1933; 2,163,403, Meacham, June 10, 1939; and 2,275,452, Meacham, March 10, 1942. All of the patents referred to above are hereby made a part of the present application as if fully included herein.

The sources of signals **120** and **130** shown in Fig.

1 and also **220** and **230** shown in Fig. 2 are illustrated in the drawing by microphones. It will be apparent to persons skilled in the art that other suitable sources of signals or complex waves may be employed such as telegraph systems, picture transmission systems, television systems, mechanical vibration pick-ups, photoelectric devices, piezoelectric devices, etc. Each of these sources is connected to the respective terminal equipments **121**, **131**, **221** and **231**. This terminal equipment represents all of the equipment connected between the sources or microphones and the transmission circuits and equipment for coding the signals to be transmitted as will be described hereinafter. This terminal equipment may include one or more of the following typical types of apparatus including amplifiers, transmission lines, switching equipment of any suitable type such as manually controlled switching equipment at a manual central office, automatic or machine or dial switching equipment such as employed in automatic central offices as well as various types of transmission apparatus including phase control apparatus, equalizing apparatus, voice controlled switching apparatus, etc. This terminal equipment may also include toll line facilities including either or both two and four-wire circuits, i. e., a single two-way or to and fro communication path or two one-way communication paths operated in opposite directions and toll line switching equipment. When the terminal equipment **121**, **131**, **221** or **231** includes switching equipment, the transmission circuits described hereinafter in detail embodying the present invention function as trunk circuits.

The complex wave form of signals from the devices **120**, **130**, **220** and **230** are transmitted to the sampling circuits **122**, **132**, **222** and **232**, respectively. Associated with the sampling circuit is a comparing circuit which together with the sampling circuit causes the magnitudes of the samples obtained by the sampling circuit to be represented by permutation code groups of signaling pulses in which each group of pulses comprises the same number of pulses and represents the magnitude of a different sample and in which each pulse may comprise one of a plurality of different signaling conditions.

From the comparing and coding circuits the signals are transmitted through the associated high frequency transmitters to the other station. After the signals have been received at these stations they are tranmitted through a phase or time delay circuit **144**, **154**, **244** or **254** which may be constructed of a suitable number of network sections of a suitable frequency range of one or more of the types disclosed in the above-identified Patent 1,770,422, granted to Nyquist.

As will be readily understood by persons skilled in the art, it is necessary that the incoming signals be maintained in a predetermined phase relation with the common equipment at the receiving stations so as to be properly decoded and translated and a complex wave reconstructed therefrom corresponding to the complex wave at the transmitting station. It is, of course, possible to provide phase or delay equipment at each of these stations for each of the transmitting and receiving channels terminating thereat.

However, as shown in Figs. 1 and 2 the phase control equipment has been provided at the receiving terminals or channels terminating at the respective stations. This arrangement has the advantage that the phase control equipment may be adjusted to compensate for the time of transmission over each of the respective channels so that it is possible to employ common control equipment at each of these stations for the operation of each of the channels terminating thereat.

After passing through the receiving and phase control equipment at the respective stations the signals are decoded by the respective decoding circuits **142**, **152**, **242** and **252** and conveyed to the respective terminal equipment **141**, **151**, **241** and **251** and then to the receiving or recording devices **140**, **150**, **240** and **250**, respectively. The terminal equipment **141**, **151**, **241** and **251** may include any of the types of apparatus or equipment described above with reference to the terminal equipment **121**, **131**, **221** and **231**.

Inasmuch as the circuits individual to each of the channels all operate in substantially the same manner, the circuits of a single channel only have been shown and described herein in detail. It will be understood, however, that similar circuits are duplicated for each of the additional channels extending between any of the stations of the system.

A control pulse generator **111** is provided at the transmitting station and connected to the output of the control oscillator **110** or the master oscillator **10**. The control pulse generator **111** is arranged to generate control pulses of both positive and negative polarity in response to the alternating current or voltage applied thereto from the control oscillator **110** or the master oscillator **10**. In the exemplary embodiment of the invention set forth herein the control pulse generator **111** simultaneously generates positive and negative control pulses for each cycle of the alternating current applied thereto. The negative control pulse generated by the control pulse generator **111** is transmitted through a delay network **112** which in the exemplary embodiment set forth herein consists of a time or phase delay network comprising impedance elements such as inductances, capacitances and perhaps resistances as pointed out above. The output of the delay network **112** is connected to a code element timing circuit **113**, and to an exponential wave generator **114** and to the sampling circuits such as **122** and **132**.

In response to each of the control pulses applied to the code element timing circuit **113** a series of code element timing pulses is generated. Each series of code element timing pulses comprises a group of positive pulses interspersed with an equal number of negative pulses. A positive pulse and a negative code pulse is generated by the code element timing circuit for each pulse of each code group of the signaling pulses as will appear hereinafter. The output of the code element timing circuit is connected to the comparing and coding circuits **123** and **133**. The exponential generator **114** is employed to generate an output wave in the form of an exponential function, the magnitude of which changes a predetermined fraction during the time interval assigned to each one of the code element timing pulses, that is, during the interval between the code element timing pulses. In the exemplary embodiment of the present invention the magnitude of the exponential wave is assumed to change by one-half of its immediately preceding value during each of the code element timing intervals. The exponential wave generator generates an exponential wave in response to each of the control pulses applied thereto from the control pulse generator **111** through the delay network **112**. The output of the exponential wave generator

114 is connected to the sampling circuits 122 and 132; to the coding and comparing circuits 123 and 133; to the decoding circuits 142 and 152; and to monitoring equipment 125, 135, 145 and 155. The outputs of the comparing and coding circuits 123 and 133 are connected to the respective transmitting amplifiers 124 or the radio frequency transmitter 134 as well as to the monitoring equipment 125 and 135 and the sampling circuits 122 and 132.

Briefly, the operation of the system is as follows: Assume, for example, that the input speech, music, or picture signal from the microphone or other device 120 has a wave form such as illustrated by the graph or curve 1301 shown in Fig. 13. Assume further that the frequency of the master oscillator 10 or control oscillator 110 is such that the control pulse is generated by the control pulse generator at the times corresponding to each of the large dots 1302 on curve 1301. At each of these times a control pulse is transmitted through the delay network 112 to the sampling circuit 122 where some electrical quantity, such as, for example, the charge on a condenser, is made proportional to the instantaneous amplitude of the complex wave 1301 at that time. In addition, the code element timing circuit and the exponential wave generator are set into operation.

The outputs of the sampling circuit and the exponential wave generator are compared in comparing and coding circuits 123. If the sample obtained from the complex wave, as described above, is greater than the amplitude of the exponential wave at the time of the positive pulse from the code element timing circuit 113, a signaling pulse is transmitted from the comparing and coding circuit 123. If the amplitude of the wave from the exponential wave generator is greater than the amplitude of the sample at this time, that is, is greater than the charge of the condenser referred to above, no signaling pulse will be transmitted at this time. Assuming, for example, that the charge or potential on the condenser in the sampling circuit will be greater than the amplitude of the exponential wave when some one or more of the positive pulses are received from the code element timing circuit. At these times pulses will be transmitted from the comparing and coding circuit 123. These pulses are transmitted through the transmitting amplifier 124 over line 6 to the receiving station. These pulses are also transmitted to the monitoring equipment 125. As an incident to the transmission of the pulses in question a potential condition is developed in the comparing circuit which is then amplified and limited and then applied to the sampling circuit. The potential applied to the sampling circuit due to the operation of the comparing circuit causes the charge on the condenser in the sampling circuit to be reduced when the corresponding pulses are transmitted. The charge is reduced by an amount represented by the pulse transmitted. Thereafter the remaining potential of the condenser is again compared with the magnitude of the exponential wave and the above process or cycle of operations repeated thus causing the transmission of a series of the pulses representing the magnitude of the sample and, hence, the instantaneous amplitude of the complex wave form. A similar series of pulses is transmitted representing the magnitude of each of the samples or instantaneous amplitudes. Each of the series of pulses is sometimes called a permutation code combination of pulses. Pulses of this type are sometimes also called binary pulses since they may be considered to represent the digits of a binary number and occupy positions corresponding to the ordinal positions of such a number.

In the exemplary embodiment described hereinafter the magnitude of each sample is represented by five code pulses, thus permitting the representation of 32 different amplitudes by each of the permutation code group of pulses. If it is desired to more accurately determine and represent the instantaneous amplitudes of the complex wave form more pulses in each code group may be employed. For example, if seven pulses are employed, 128 different amplitudes may be represented. In other words, 2^n different amplitudes may be represented by the permutation of the n pulses of two different types, i. e., current and no current, or positive and negative current. It will be readily apparent to persons skilled in the art that in order to change the number of code elements representing each amplitude it is only necessary to change the number of pulses generated by the code element timing circuit 113 in response to each of the control pulses transmitted through the delay network 112 and to change the constants of the exponential circuit and perhaps other circuit constants.

After all of the pulses of a given permutation or code group of pulses have been transmitted, another control pulse from the control pulse generator 111 will cause the equipment to sample a complex wave form at a succeeding interval of time and the above process is repeated. The interval of time between the samples of the complex wave together with the number of different amplitudes transmitted representing each of the instantaneous amplitudes determine the accuracy and fidelity of the reproduction of the complex wave form at the receiving station as will be readily apparent to persons skilled in the art.

Furthermore, it is necessary to sample the complex waves at a rate at least twice the highest frequency desired to be transmitted and represented in the reconstructed wave form at the receiving end of the system.

Monitoring equipment 125 is provided at the transmitting station and is connected to the control pulse generator 111, to the exponential wave generator 114 and to the output of the comparing and coding circuit 123 and is arranged to decode each group of pulses and generate a pulse having an amplitude proportional to the instantaneous amplitude represented by the code groups of pulses transmitted from the transmitting station. Each of the pulses of varying amplitude generating in the monitoring circuit is applied to a low-pass filter and then to some receiving device or indicator 126 so that the operation of the system may be monitored at the transmitting station. A monitoring circuit is shown in Fig. 1 for each channel. It will be understood by persons skilled in the art that a monitoring circuit may and usually will be common to a number of the channels and connected to any desired channel by a key, a plug and jack, or other suitable equipment.

The station shown in Fig. 2 is similarly provided with a control pulse generator 211 which generates a pulse in response to each oscillation received over channel 5 and oscillator 210. However, in the event that channel 5 becomes in-operative the control pulse generator **211** will still be controlled by oscillator **210**. Consequently it may be possible to operate the system for a considerable period of time without receiving a synchronizing or controlling frequency over channel **5**.

The receiving station is likewise provided with a delay network **212**, code element timing circuit **213**, and exponential wave generator **214** which operate in substantially the same manner as described above with reference to the corresponding equipment at the transmitting station. The output of the exponential wave generator is connected to the decoding circuit **242** to which is also applied the received signals after being amplified by amplifier **243**. The decoding circuit **242** response to the pulse groups received to produce pulses of differing amplitude depending upon the amplitude of the exponential wave at the time the individual pulses are received. The pulses of differing amplitude are then applied to a low-pass filter where the complex wave form is reconstructed and regenerated. The output of the terminal equipment **241** is transmitted to the receiving device **240**. Equipment **241** may include any or all of the equipment mentioned above with reference to terminal equipment **221**. It will be readily understood by persons skilled in the art that equipment **221** and **241** may each include any of the different devices or equipment referred to above but that both of these devices do not necessarily have to include the same types of equipment but may do so.

Monitoring equipment **245** is provided at the receiving station and enables the attendants to check the operation of the receiving apparatus. This equipment, as shown in Fig. 2, is individual to the transmission path **6**. It also may be common to all the paths or any portion thereof terminating at the station of Fig. 2 in which case it will be switched to the transmitting or receiving end of any path over which it is desired to observe the transmission.

Reference will now be made to Figs. 3 to 10 inclusive, when arranged as shown in Fig. 12, together with Figs. 13 and 14, which set forth in detail the various circuits and apparatus and the methods in which they cooperate to form a typical exemplary system embodying the present invention.

Figs. 3 to 7 inclusive, illustrate in detail common equipment employed at one station at which it is assumed the complex wave form is applied to the system. This station will frequently be called a transmitting station hereinafter.

Figs. 8, 9 and 10 show the equipment as a second station at which complex wave form is reconstructed and delivered to utilization circuits and equipment. This station will frequently be called hereinafter the receiving station. In addition, Figs. 3 to 10 inclusive, show only a single one-way communication path and the equipment thereof in addition to the equipment common to a plurality of paths.

Figs. 3 and 5 show details of the circuit at the transmitting station which are common to a number of transmission paths, while Fig. 8 and the upper portion of Fig. 9 show similar circuits at the receiving station. The other figures show equipment which is individual to each transmission path. It will be obvious to persons skilled in the art that to provide additional communication paths in either direction between the two stations it is only necessary to provide additional equipment similar to the equipment already shown in the drawings for each additional transmission path.

In order to better understand the operation of the system, the common equipment, shown at the top of Figs. 1 and 2 in diagrammatic form and shown in greater detail in Figs. 3, 5, 8 and the upper portion of Fig. 9, will be described at length.

Figs. 5 through 10 have not been complicated by showing the connections of the filaments or heaters of the various tubes to a suitable source or sources of power because persons skilled in the art will understand that the filaments or heaters are supplied with power during the operation of the system.

A master oscillator **510** and a second oscillator **525** are shown in Fig. 5. If the master oscillator **510** is located at the transmitting station shown in detail in Figs. 3, 4, 5, 6 and 7, the local oscillator **525** may be dispensed with. However, in the case of master oscillator **510** located at some other station, such as a master frequency standard for a large number of stations, systems, or for the entire country, both oscillator **510** and the local oscillator **525** will usually be employed. Master oscillator **510** may be of any suitable type such as the type disclosed in the above-identified Meacham or Marrison patents. The local oscillator **525** will then include some control apparatus for maintaining its frequency in synchronism with the frequency of the master oscillator **510** similar to the equipment described in greater detail in the above-identified patents. Oscillator **525** is connected over a synchronizing line **580**, which is shown in Figs. 5 and 8 as a coaxial line. Line **580** extends to the receiving station shown in Figs. 8, 9 and 10. Here the coaxial line **580** terminates in the local oscillator **810**, which is similar to the oscillator **525**. While the synchronizing line **580** is shown as a coaxial line, persons skilled in the art will readily understand that any suitable type transmission path may be employed which is capable of transmitting the synchronizing frequency employed.

Control pulse generator

The local oscillator **525** or the master oscillator **510** is connected to a multivibrator circuit comprising tube **511**. The multivibrator circuit **511** operates to generate square waves which are usually of the same fundamental frequency as is received from oscillator **525** or **510**. Multivibrator circuits are well known in the prior art. Typical multivibrator circuits suitable for use in the present system are described in greater detail in United States Patents 1,744,935, granted to Van der Pol January 28, 1930, and 2,022,969, granted to Meacham on December 3, 1935, and in an article by Hull and Clapp, published in the Proceedings of the Institute of Radio Engineers for February 1929, pages 252 and 271. See also section 4–9 entitled "Multivibrator," on page 182 of "Ultra-high Frequency Techniques," by Brainerd, Kochler, Reich and Woodruff. The output of the multivibrator **511** is coupled through condenser **512** and resistance **513** to amplifier tube **514**.

Condenser **512** is made variable so that it, together with resistance **513**, may be employed to control the length of the synchronizing pulse derived from multivibrator circuit **511**. If the time constant of condenser **512** and resistance **513** is large the output pulse will be relatively long, whereas, if the time constant of condenser **512** and resistance **513** is small or short, the output pulse will be short. In a typical embodiment of the present system the size or magnitude of the condenser **512** and resistance **513** were selected to produce an output pulse of approximately two microseconds duration.

Condenser **512** and resistance **513** are coupled to the control grid of tube **514**. It should be noted that resistance **513** is connected between the grid of tube **514** and the positive B battery potential instead of the ground or some negative value as in the usual case. By connecting resistance **513** between the grid and positive B battery potential or some other high positive battery, the sides of the pulses are made steeper, the generation of very short pulses is improved and the more satisfactory operation of the system is obtained.

The ouput of the amplifier tube **514** is in turn coupled to tubes **515** and **516**. Tubes **514**, **515** and **516** are amplifier tubes which are overloaded by the magnitude of the pulses applied to them so that these tubes tend to limit the magnitude of the pulse repeated through them and at the same time tend to make it square in wave shape. Amplifiers of this type are sometimes called "limiting" and at other times "clipping" amplifiers because they limit or clip off or suppress the upper portion of the input waves applied to their grids or control elements. A single stage limiter is shown in Figs. 8–6 on page 282 and described on page 283 of "Ultra-high Frequency Techniques," by Brainerd, Kochler, Reich and Woodruff, first published in July 1942 by D. Van Nostrand Company, Inc. The ouput of tube **516** is coupled to a power tube which is employed to supply sufficient power for the output pulses of the circuit so that they may be employed to control other circuits of the system. The output of tube **517** is arranged to supply both positive and negative pulses as shown by the graphs **521** and **523** in Fig. 5. The negative pulses are obtained from the anode resistor **526** connected to the plate or anode of tube **517**, while the positive pulses are obtained from the cathode resistor **519** connected to the cathode of tube **517**.

It will be obvious to persons skilled in the art that in cases where a large number of circuits are supplied from the pulse generator shown in Fig. 5, additional output stages may be connected in parallel with tube **517**, having their input circuits connected in parallel with the input circuit of tube **517**, or they may be driven by this tube by having their inputs connected to the output circuit of this tube. Such arrangements are well understood and frequently employed where one tube does not supply sufficient output energy.

The negative pulses from the plate of tube **517** pass through a delay network **522** where they are delayed slightly in time with respect to the positive pulses **521**. The purpose of this delay network will become apparent hereinafter. Delay network **522** may be of any suitable type employing reactive elements in any well understood manner as in the art pointed out above. The output of the pulse generator, as shown in Fig. 5, is diagrammatically indicated by the small curve **521** for positive pulses and curve **523** for negative pulses, in order to facilitate the reading and understanding of the operation of the circuit.

In order to further facilitate the understanding of the operation of the system, reference will also be made to Figs. 13 and 14 which show graphs of the wave form of the voltage of currents at various places in the system under certain assumed conditions. Curve **1301** of Fig. 13 represents a complex wave form of a type suitable for transmission over the system described herein. As will be described hereinafter, the magnitude or amplitude of this wave form is sampled or measured at frequently recurring intervals of time. For purposes of illustration, the operation of the system will be described in detail for one such measurement, which is assumed to be made at the point **1303**. As shown in Fig. 13 by dots **1302**, this wave form is sampled at frequent intervals represented by the dots **1302**. The frequency of the sampling determines the highest frequency component of the complex wave which may be represented by the successive permutation code signals and thus reproduced at the receiving end of the system.

Vertical lines **1304** in the next set of curves represent positive pulses **521** supplied by the pulse generator shown in Fig. 5. Likewise, the vertical lines **1305** represent the negative pulses generated by the pulse generator shown in Fig. 5. As shown in Fig. 13, the negative pulses **1305** are delayed for a short interval of time and consequently follow pulses **1304**. This is apparent in Fig. 13 when it is assumed that time increases in the positive direction to the right. It is further assumed in the exemplary system described in detail herein that samples of the complex wave are arranged at a rate of approximately 8,000 times a second. Persons skilled in the art will understand that any other suitable frequency may be employed so long as this frequency is appreciably higher than the highest frequency component of the complex wave necessary or desirable to transmit to the distant station. In other words, the frequency of oscillators **510** and **525** is either 8,000 cycles a second or else frequency changing apparatus is connected between them and the multivibrator **511** in a manner well understood in the art, so that the multivibrator **511** operates at a frequency of approximately 8,000 cycles a second. In other words, the positive pulses **1304** as well as the delayed negative pulses **1305** are supplied by the pulse generator shown in Fig. 5 at the rate of 8,000 per second. Consequently, there are 125 microseconds between the pulses **1304**. Similarly, a period of 125 microseconds elapses between the pulses **1305**. The negative pulses from the delay network **522** are supplied to the amplifier tube **310** in Fig. 3 over lead **524** where they are amplified and changed to positive pulses due to the operation of the amplifier tube **310**. Tube **310** is shown in Fig. 3 as a pentode tube. It will be obvious to persons skilled in the art that this tube may be replaced by any suitable triode tube or other multielement tube having the desired or necessary power or current capabilities.

Code element timing circuit

The output of tube **310** is connected to the code element timing circuit comprising tubes **311**, **319**, **320** and **321**. Tube **311** is normally biased so that substantially no current flows to the anode circuit of this tube. When the amplified and delayed synchronizing pulse is applied to the grid of tube **311** from the output of tube **310** it causes the grid of this tube to become positive for the duration of this pulse. During this time condenser **312** in the cathode circuit of tube **311** will receive a positive charge. Curve **1306** of Fig. 13 shows the potential of the upper terminal of condensers **312**. The short positive section designated **1320** above the delayed synchronizing pulse **1305** represents the positive potential applied to the upper terminal of condenser **312** for the duration of this synchronizing pulse. Thus, during the application of the delayed synchronizing pulse **1305** to the grid of tube **311** after it has been changed into a positive pulse by tube **310**, energy is stored in the oscillating circuit comprising condenser **312** and inductance **313**. At the end of the synchronizing pulse the grid of tube **311** again becomes sufficiently negative so that substantially no current flows in the cathode circuit of this tube. The tube, therefore, does not thereafter materially alter or change the currents or potentials of the oscillating circuit until the next synchronizing pulse is applied to the grid thereof.

At the end of the synchronizing pulse the oscillating circuit comprising condenser **312** and inductance **313** starts to oscillate in a manner shown in curve **1306** of Fig. 13. As shown in Fig. 13, the current in the resonant circuit comprising condenser **312** and inductance **313** makes substantially six complete oscillations between the applications of the synchronizing pulses to the grid of tube **311**. Thus, after substantially six cycles the oscillations of the resonant circuit comprising condensers **312** and inductances **313** are started over in proper phase relationship with oscillator **525**.

The upper terminal of the oscillating circuit which is connected to the cathode of tube **311** is also connected to the grid of tube **319**. Tube **319** operates as a cathode follower since the output resistance comprises resistance **314** connected in the cathode circuit of tube **319**. As is well understood by persons skilled in the art, tubes acting as so-called cathode "follower" stages have an extremely high impedance in their input circuit. Consequently, the connection to the grid of tube **319** does not materially alter or affect the oscillations of the resonant circuit as described above. Such properties as well as other properties of vacuum tubes operated as cathode followers are well known to persons skilled in the art (see "The Cathode Follower," by C. E. Lockhart, parts 1, 2 and 3, published in "Electronic Engineering" for December 1942, February 1943 and June 1943, respectively). The foregoing publications are hereby made part of the present application as if fully included herein and apply to the operation of the cathode follower tube **319** as well as to the other cathode follower tubes described hereinafter. Tube **319** is also provided with a so-called decoupling network in its anode circuit comprising resistance **333** and condenser **334**.

The output of cathode follower tube **319** is coupled through a coupling network comprising resistance **315** and condenser **316** to the grid of the left-hand section of tube **320**. The coupling network comprising resistance **315** and condenser **316** is provided to cause the grid of the left-hand section of tube **320** to follow the potential applied to the cathode of tube **319** with as little distortion as possible. Condenser **316** is employed to compensate for the input capacity of the left-hand section of tube **320**. When the ratio of the condenser **316** to the input capacity of tube **320** is the same as the ratio of resistance **315** to resistance **331**, the potential of the grid of the left-hand section of tube **320** is substantially a constant fraction of the potential of the cathode of tube **319** independently of the applied frequency. The foregoing relationship holds so long as the constants of the various circuit elements employed as well as the constants of the tubes employed remain substantially constant and independent of frequency.

The output of the left-hand section of tube **320** is coupled to the right-hand section of tube **320** and this section in turn is similarly coupled to the input of tube **321**. The two sections of tube **320** are biased to operate as an overloaded or limiting amplifier and cause the output hignals to be substantially flat-topped or square. Tube **321** will usually be of a type which is capable of furnishing sufficient power, current or voltage of the desired wave forms. Graph **1307** of Fig. 13 shows the output wave form of the code element timing circuit. As shown in Fig. 13, the tops and bottoms of the waves are shown to be flat and the corners square. As is well understood by persons skilled in the art, the corners will generally be rounded somewhat in practice and the tops and bottoms of the waves will not be flat. However, the slight rounding of the wave form is a function of the various parameters of the circuit and may be reduced to any desired degree. Inasmuch as this rounding does not materially interfere with the operation of the circuit as described hereinafter and as an aid in drawing the curves, the graph **1307** has been shown as a square wave with square corners. In addition, the graph **1307** has been shown as comprising waves having equal tops and bottoms. That is, the top and bottom of the square wave is of substantially the same length or time duration as shown in Fig. 13. Such an arrangement is not necessary because the top and bottom of the wave need not be the same length but may vary in length over a considerable range without adversely affecting the operation of the system. However, in an effort to simplify the drawing and aid the understanding of the invention, both the top and bottom of the wave have been shown in Fig. 13 as being of equal length.

Exponential circuit

In addition to the code element timing circuit shown in Fig. 3, an exponential circuit is also provided comprising tubes **323** and **331**. As shown in Fig. 3, tube **323** is a so-called twin triode tube. However, both sections of this tube are shown connected in parallel in order to secure the desired characteristics or current carrying capacity. This tube, therefore, is the full equivalent of any suitable three-element tube and may be so considered.

The output of the amplifying tube **310**, which amplifies and inverts the delayed synchronizing pulse, is coupled to the grid circuit of tube **323**. The cathode circuit of tube **323** comprises a condenser and resistance network comprising condenser **325** and resistance network **326** and **324**.

Tube **323** is normally biased so that substantially no current flows in its anode circuit. When the positive delayed synchronizing pulse is applied to the grid of this tube it will cause current to flow in the anode-cathode circuit of this tube, which in turn will cause the upper terminal of condenser **325** to be charged to a relatively high positive potential. When the synchronizing pulse is removed, the upper terminal of condenser **325** will start to discharge through resistance **326** and **324**. The potential of the upper terminal of condenser **325** will therefore decay or fall in accordance with the well-known exponential law. In other words, when the value of the resistances **324** and **326** and the value of condenser **325** are both fixed for any given set of operating conditions, the curve of the potential of the upper terminal of condenser **325** against time follows the well-known exponential law. See section 123, beginning on page 453 of "Principles of Electrical Engineering," by Timbe and Bush, published by John Wiley and Sons, Incorporated, 1923 (first edition). This publication is hereby made a part of the present application as if fully included herein.

Although many suitable values of the relative magnitudes of condenser **325** and resistances **324** and **326** could be chosen to provide many different time constants suitable for operation in circuits described herein, in the exemplary embodiment employed in the present invention, suitable time constants for this network comprising resistances **324** and **326** and condenser **325** has been chosen so that the potential of the upper terminal of condenser **325** decreases one-half its value during each of the signaling pulse intervals. That is, the time constant of the condenser resistance network comprising condenser **325** and resistances **324** and **326** are so selected that the potential of the upper terminal of condenser **325** at the end of any and all of the pulse intervals will be equal to substantially one-half the value of the potential of the upper terminal of this condenser at the beginning of the respective pulse intervals.

The grid of the output tube **331** is connected to the junction point of resistances **326** and **324**. Thus, it is possible to select the desired fraction of the voltage upon the upper terminal of condenser **325** for controlling tube **331**. Tube **331** acts both as a pulse amplifier tube and also as a cathode follower tube. Thus, both positive and negative exponential waves may be obtained from the output circuits of tube **331**. The exponential wave obtained across the output cathode resistor **329** is substantially of the same wave form as the potential wave upon the upper terminal of condenser **325**. Such a curve is illustrated by graph **1308** in Fig. 13. The output obtained from the anode of tube **313** will be inverted and appear as curve **1309** of Fig. 13.

Compression and sampling circuit

Microphone **420** represents any suitable source of complex waves or signals to be transmitted as described above. The source of complex waves **420** is connected through terminal equipment **421** to transformer **410**. The secondary of the transformer **410** is connected to potentiometer **412** and also to a non-linear circuit element **411**. The function of these two elements is to compress the amplitude of the complex wave received from terminal equipment **421**. The non-linear element **411** may be of any suitable type and may include any suitable elements such as cuprous-oxide rectifiers, selenium rectifiers, thyrite, etc. As the input potential becomes higher in value, the resistance element **411** will decrease in value, thus tending to reduce the variation of magnitude of the signaling voltages delivered to potentiometer **412**. The movable contact member of potentiometer **412** is connected to the control element or grid of the left-hand section of tube **416**. Thus by varying the potentiometer **412** and making a compensating change in the signal level received from the terminal equipment **421** the amount or degree of compression can be easily and readily varied. If the movable contact of potentiometer is set near the bottom and the signal level from the equipment **421** raised, the compression of the signals as applied to the grid of the left-hand section of tube **416** is increased. If, however, the movable member is moved up and the signal level from **421** reduced to compensate for the change of the potentiometer, then the signals applied to the grid of the left-hand section of tube **416** will be less compressed.

If no compression is desired, key **450** will be operated. With key **450** operated the compression equipment is disconnected from the signal transmission path and the signals are conveyed directly from the terminal equipment **421** to the grid of the left-hand section of tube **416** without compression or other change.

The grid or input of the right-hand section of tube **416** is connected to the negative synchronizing lead **524** from the delay circuit **522**. The right-hand section of tube **416** is biased so that normally considerable current flows in the output or anode-cathode circuit of tube **416**. As a result of this current flowing through the decoupling resistance **419** and the anode or output resistance **418** of tube **416**, a relatively low value of potential is applied to the anodes of the twin triode tube **416**. Consequently, a relatively low potential is applied to the grid of tube **417**. As a result, substantially no current flows in the anode-cathode circuit of tube **417** at this time. However, upon the application of a negative synchronizing pulse to the grid of the right-hand section of tube **416**, substantially no output current flows in the anode circuit of the right-hand section of tube **416**. Consequently, the current flowing through resistance **418** falls to a value determined by the grid potential of the left-hand section of this tube, which is in turn determined by the instantaneous amplitude of the complex wave applied to the grid of the left-hand section of tube **416** at the instant of time that the delayed negative synchronizing pulse is applied to the grid of the right-hand section of tube **416**. As a result, the potential applied to the grid of tube **417** will rise to a value accurately determined by the instantaneous amplitude of the complex wave applied to the grid of the left-hand section of tube **416** at this time. As a result, current will flow in the anode-cathode circuit of tube **417** and thus charge the upper terminal of condenser **426** to a value determined by said instantaneous amplitude of the applied complex wave form. Upon the completion of the application of the synchronizing pulse to the grid of the right-hand section of tube **416**, the right-hand section of this tube will again conduct current and lower the potential of grid of tube **417** to such a low value that substantially no further current flows in the cathode circuit of tube **417**. The upper terminal of condenser **426** is connected to the grid circuit of tube **431**, which tube acts as a cathode follower and tends to accurately repeat the wave form or potential of the upper terminal of condenser **426**. Tube **431** acts as a cathode follower tube since its output is obtained from the cathode resistor **433**. Consequently, the grid of tube **431** presents an extremely high impedance to the condenser **426** and will not therefore appreciably alter or interfere with the potential of the upper terminal of condenser **426**.

Comparing circuit and coding

The cathode of tube **431** is coupled through coupling network **432** to the input control grid of tube **434**. Consequently, the potential of the control grid of tube **434** accurately follows the potential of the upper terminal of condenser **426**. Tube **439** has its control grid coupled through condenser **438** to the anode of tube **331**. The constants of coupling condenser 438 and resistance 442 are such that the potential of the grid of tube 439 accurately follows the potential of the anode of tube 331. As pointed out above, the potential of the upper terminal of condenser 325 follows the curve 1308. Due to the inverting action of tube 331 the potential of the anode of tube 331 and thus the potential of the grid of tube 439 follows the curve illustrated by graph 1309 of Fig. 13 which is the inverse of curve 1308.

Tubes 434 and 439 operate as a pair of comparing tubes having a common output circuit comprising resistance 437. The decoupling network comprising resistance 436 and condenser 443 is also provided to prevent interaction between the comparing tubes 439 and 434 and the other tubes of the system through the common source of anode potential. Thus, the currents through tubes 434 and 439 are added together in resistance 437. Inasmuch as the grid of tube 434 has applied to it the potential which is proportional to the potential of the upper terminal of condenser 426, the anode or output current flowing through tube 434 will also be proportional to the potential of the upper terminal of condenser 426. Likewise, the anode current flowing through tube 439 proportional to the grid potential applied to this tube is illustrated by curve 1309 of Fig. 13.

We will now assume that the sample obtained at point 1303 of curve 1301 causes a current to flow in the output circuit of tube 434 which is represented by the segment 1321 of the graph 1310 shown in Fig. 13. Similarly, the current flowing in the output circuit of tube 439 is represented by graph 1309, as pointed out before. The segment 1322, which is the sum of the segment 1321 and curve 1309, represents the total current flowing through the output resistance 437. The output of tubes 434 and 439 as combined in resistance 437 is coupled through the coupling network 722 to the control element of tube 711. Tube 711 is biased so that this tube will conduct current, when the current through the output resistor 437 is below a fixed value such as represented by line 1330 of Fig. 13. The lower the total current flowing through resistance 437 the lower will be the potential drop across this resistance and thus the higher in a positive direction will be the potential applied to the control element or control grid of tube 711. When the segment 1322 representing the combined anode currents of tubes 434 and 439 exceeds the value of current represented by line 1330, as shown at point 1323 the potential of the grid of tube 711 will fall below the cut-off value for this tube. Consequently, at this time no further current will flow through the tube 711.

The output of tube 711 is supplied to the tandem amplifying tubes 712 and 714, which tubes act as limiting amplifiers and cause either one of two different conditions to be produced in the output circuit of tube 714 as indicated by graphs 1312, etc. When tube 711 is conducting, tube 714 is also conducting and a relatively small value of potential is developed in the output of tube 714. The other condition occurs when tube 711 is cut off under which circumstance tube 714 is also cut off and a relatively high voltage is produced in its output circuit. The output circuit of tube 714 is connected to a control element, usually called a suppressor grid, of tube 428. Tube 428 normally has a bias applied to its various control grids, such that a positive pulse has to be applied simultaneously to both the control grid and suppressor grid in order to cause any current to flow in the anode circuit. The function of tube 428 is to reduce the charge on condenser 426 under such conditions as will cause the tube to conduct as will appear from the later description.

Assuming now that at the time the synchronizing pulse 1305 is applied to the system, as described above, the amplitude of the complex wave will produce a current 1321 in the output circuit of tube 434. Immediately upon the cessation of the synchronizing pulse 1305 the output of the code element timing circuit will change from a negative to a positive value, as shown by segment 1329 of graph 1307. At this time the output of tube 714 will be below the positive value required to be applied to the suppressor grid to cause tube 28 to draw current and consequently upon the application of a positive pulse from the code element timing circuit to the control grid of tube 428 no current will flow in the output circuit of this tube. Consequently, the potential upon the upper terminal of condenser 426 is not changed at this time.

The output of the code element timing circuit is also coupled through pulse-shaping apparatus 728 and coupling condenser 725 to the suppressor grid of tube 715. This pulse-shaping apparatus may include one or more electron devices such as tube 730 as well as various types of pulse-shaping and control networks. As shown in Fig. 7, tube 730 is connected as a cathode follower tube with its input circuit connected through the coupling condenser 731 to the output of tube 321 of the code element timing circuit. While it is not essential that condenser 731 and resistance 732 differentiate the wave from the code element timing circuit, the values of these elements in one embodiment of the invention have been so chosen that they do differentiate the wave 1307 and cause a short positive pulse to be applied to the grid of tube 730 each time the code element wave changes in a positive direction. This positive pulse when applied to the grid of tube 730 causes a charge to be stored upon condenser 734. The charge upon condenser 734 is then dissipated through network 733 of which condenser 734 may or may not form a part. Network 733 is designed to accurately control the length of the output pulse as well as any other desirable or necessary characteristic thereof.

The pulse-shaping network 728 is shown in Fig. 7 in symbolic form and is not limited to the specific form shown in Fig. 7. Likewise, the electron device is also shown in symbolic form and may include many more tubes, circuits and devices including "limiting" or "clipping" tubes and circuits with appropriate coupling and power supply circuits, including differentiating as well as pulse lengthening arrangements. Similarly, network 733 may include one or more suitable sections and may include transmission lines, sections thereof, artificial lines or other networks which simulate lines. These lines may be appropriately terminated to secure the desired reflections or other effects.

At the time the first shaped pulse is applied to the suppressor of tube 715, the control grid thereof will be negative under the assumptions as described above. Consequently, no pulse is transmitted over the transmission channel to the receiving station at this time.

Thereafter the currents flowing through the output resistance 437 will increase as shown in curve 1322 and at the point 1323 the voltage across resistance 437 will rise sufficiently that current will cease flowing through the output circuit of tube **711**. Consequently, the output potential of tube **714** will rise to a positive value as shown by the graph **1312**. The circuits then continue to operate as described above until the output of the code timing circuit again changes from negative to positive, as illustrated by the segment **1331** of graph **1307**. At this time a sharp positive pulse is applied to the control grid of tube **428** and to the suppressor grid of tube **715**. The constants of the coupling condenser **429** and resistance **440** are such that they serve to differentiate the output wave **1307** from the code element timing circuit and generate very short positive pulses when the output changes from negative to positive or from no current to a positive current. At the time this second positive pulse is applied to the suppressor grid of tube **715** through the pulse-shaping apparatus **728**, the control grid of tube **715** will be positive because the output of tube **714** is positive at this time, as shown by graph **1312** and described above. Consequently, a pulse having substantially the same wave shape as the output from the pulse-shaping apparatus **728** and represented by the line **1315** will be transmitted over the transmission path **780** through the output tube **720**.

At this time the screen of tube **428** will have a value equal to one-half of its maximum value because the potential on the screen of tube **428** follows curve **1308** due to the fact that it is coupled through coupling condenser **430** and resistance **441** to the cathode of tube **331**, the potential of which is directly proportional to the potential of the upper terminal of condenser **325**. Under these circumstances upon the application of a positive pulse to the control grid of tube **428** the charge on condenser **426** will be reduced by an amount equivalent to one-half of its highest maximum value. Thereafter the sum of the output currents of tubes **434** and **439** will fall and start to rise upon the segment **1311**, because the output of tube **434** falls as illustrated by the segment **1310**. At this time the output of tube **714** will also reverse and become substantially zero, as shown by graph **1312**. At the time the third positive pulse is applied to the control grid of tube **428** and the grid of tube **715**, the output of tube **714** will still be negative. Consequently, no pulse will be transmitted and the potential of the upper terminal of condenser **426** will not be altered at this time. If the combined output currents had exceeded the reference value **1330** at this time, a pulse would have been transmitted as represented by the dotted line **1316**. However, since under the assumed conditions the combined output does not exceed the reference current **1330**, no pulse is transmitted at this time.

At a somewhat later time at point **1325** the combined output current of tubes **434** and **439** exceeds the reference value **1330**, at which time the output of tube **714** again becomes positive. When the next timing pulse is applied to the grid of tube **428** and the suppressor of tube **715**, a pulse will be transmitted over the transmission path **780** and the charge upon the upper terminal of condenser **426** will be reduced. Inasmuch as the potential of the screen of tube **428** is one-eighth of its original value at this time, one-eighth of the total possible maximum charge will be removed from condenser **426** at this time. Thereafter the circuits operate in the same manner as described above and transmit the remaining two pulses under control of the magnitude of the charge remaining on condenser **426** and thus under control of the magnitude of the complex wave at the time it was sampled. After the transmission of the final pulse **1319** another synchronizing pulse **1305** will be applied to the system and the above cycle of operations repeated.

During each cycle of operations another series of pulses will be transmitted which represent the magnitude of the complex wave at the time the synchronizing pulses are applied to the system. This action is repeated for each of the synchronizing pulses applied to the system and a permutation code series of pulses transmitted over the transmission path **780** in response to each of the synchronizing pulses.

The output of tube **715** is also coupled to the input of a monitoring circuit equipment shown in Fig. 6, which is provided to enable the attendants at the transmitting station to monitor the output signals in order to test and adjust the system and to determine its proper operation. This monitoring equipment is similar to certain of the receiving equipments shown at the receiving stations and operates in substantially the same manner. Inasmuch as it will be described with reference to the operation of the equipment at the receiving station, a detailed description of the operation of this apparatus will not be described at this point.

Pulse transmission system

The pulses transmitted by tube **715**, as described above, are transmitted through amplifying or coupling tube **720** to coaxial cable **780**. The amplifying tube or coupling tube **720** is connected as a cathode follower, because cathode follower tubes have relatively low output impedance for matching the low impedance of a coaxial cable.

As shown in Figs. 7, 9 and 10 the transmission path from the transmitting station of Figs. 3 through 7, inclusive to the receiving station shown in Figs. 8 through 10, inclusive comprises a coaxial cable. As pointed out above, this transmission path may be of any suitable type or combinations of different types. In addition, this transmission path may include various types of amplifiers, gain control devices, phase control devices and repeaters. Inasmuch as all of this equipment operates in its normal and usual manner when incorporated in the present system and inasmuch as the operation of this type of equipment is well understood by persons skilled in the art, it is unnecessary to repeat the detailed description of the equipment and method of operation at this point. As pointed out above, a phase correction network **930** is included in the transmission path to control the over-all time of transmission of pulses or signals from the transmitting station to the receiving station, so that the common equipment at the receiving station shown in Fig. 8 may be employed to control the channel equipment for a number of channels from different stations having different transmission times. By including the phase control network which, in effect, controls the over-all transmission time, it is possible to delay the signaling pulses so that they will arrive at such times as to be properly synchronized with the synchronous equipment at the receiving station. Of course, as pointed out hereinbefore, this phase control equipment may be located at the transmitting station, or part of it may be located at the transmitting station and another part at the receiving station. Furthermore, where the synchronizing equipment is individual to a group of channels from a given station, all of which have substantially the same transmission delay time, the phase control equipment may be connected in series with the synchronizing path from that station instead of in each of the individual channels. However, in the system set forth herein a phase control system is provided for each of the channels between each of the respective stations.

Decoding and receiving circuits

After the signals pass through the phase control equipment 930 they are applied to the input circuit of an amplifier tube 910. Amplifier tube 910 is connected with its grid grounded and the input signal applied across the cathode resistor. This arrangement is employed because the input impedance of a tube connected in this manner is relatively low and thus furnishes a proper termination for a coaxial cable circuit or the phase control equipment associated therewith.

As pointed out hereinbefore, the receiving station is also provided with a control pulse generator shown in Fig. 8, which is similar to the control pulse generator shown in Fig. 5 and provided at the transmitting station. The control pulse generator shown in Fig. 8 is arranged to generate both a positive and a negative control pulse for each permutation code group of pulses in the same manner as the control pulse generator described hereinbefore with reference to Fig. 5. The negative output of the control pulse generator passes through a delay network 822 which is similar to the delay network 522 and delays the negative control pulse by an amount similar to the delay by network 522. The delayed negative control or synchronizing pulse is applied to the input circuit of tube 925 which amplifies this pulse and inverts its phase or polarity. The delayed pulse thus becomes a positive pulse and as such is applied to the grid or control element of tube 926.

Tube 926 is normally biased so that no current flows in its anode-cathode circuit. However, when a positive control pulse is applied to its grid, tube 926 will permit current to flow in its anode-cathode circuit and charge the upper terminal of condenser 927 to a relatively high positive potential. Upon the termination of the synchronizing pulse applied to the grid of tube 926 this tube again ceases to conduct and does not therefore materially alter or affect the potential upon the upper terminal of condenser 927. Also upon the termination of the synchronizing pulse applied to the grid of tube 926 the upper terminal of condenser 927 starts to discharge through the resistance 940 and discharges in accordance with well-known exponential law, as described with reference to condenser 325.

The upper terminal to condenser 927 is connected to the input circuit of a cathode follower tube 931 similar to tube 331. Two output circuits are provided for the output of the cathode follower tube 931, which may be connected thereto by means of the respective switches 928 and 929 which are shown closed in the drawing. It is obvious that in case it is desired to disable the receiving equipment or the monitoring equipment described hereinafter, either or both of these switches may be opened by the attendant.

The exponential voltage wave generated by condenser 927 is applied to the screen of tube 1011. It is also connected to the screen of tube 913. The coupling between the output of tube 931 and the screens of tubes 913 and 1011 is such that the potential of the screen of these two tubes is substantially directly proportional to the voltage of the upper terminal of condenser 927.

The delayed positive pulse as amplified by tube 925 is also applied to the grid or control element of tube 1010. Tube 1010 is normally biased so that it does not conduct current. In other words, the tube is normally biased beyond cutoff so that no current flows in its anode-cathode circuit. When the delayed positive synchronizing pulse is applied to this grid, however, current will flow in the anode-cathode circuit of this tube and cause the upper terminal of condenser 1014 to be charged to a relatively high positive potential. Upon termination of the synchronizing pulse tube 1010 again becomes nonconducting and does not materially affect the potential of the upper terminal of condenser 1014 until another synchronizing pulse is applied to its grid circuit.

The received signals, as amplified by the coupling or amplifying tube 910, are applied to the grid of tube 1011. As pointed out above, the screen of this tube has applied to it the exponential wave generated by the discharge of condenser 927 through the resistance 940 which has a wave form as shown by graph 1401 of Fig. 14. Under the conditions assumed at the transmitting station, no first pulse will be transmitted immediately after the synchronizing pulse 1405. At a later time, illustrated by line 1415, a pulse will be received at the receiving station. At this time the magnitude of the exponential wave is one-half of its maximum value, that is, one-half the value it had immediately following the termination of the synchronizing pulse. Consequently, when the received pulse 1415 is applied to the grid of tube 1011, the condenser 1014 will discharge so that the potential of the upper terminal of this condenser will fall to one-half of its maximum or previous value. The variation of potential on the upper terminal of condenser 1014 is illustrated in Fig. 14. Segment 1421 represents the potential of the upper terminal of condenser 1014 after the synchronizing pulse has terminated and before pulse 1415 is received. Upon the receipt of pulse 1415 the potential of the upper terminal of condenser 1014 falls to one-half the value, which is represented by segment 1422 of the graph in Fig. 14. Under the assumed conditions, a spacing pulse, a no-current pulse, or a pulse of no current corresponding to pulse 1316 or 1416 is transmitted and received over this system. Consequently, the potential on the upper terminal of condenser 1014 will remain constant at this time. However, a fourth pulse is transmitted and received, so that at this time the potential of the upper terminal of condenser 1014 is again decreased at this time by an amount equivalent to one-eighth of the maximum potential applied to the upper terminal of condenser 1014. This potential is represented by the segment 1423 of Fig. 14. The next pulse is of a spacing character, i. e., a pulse of no current or negative current. Consequently, the potential of the upper terminal of condenser 1014 is not altered at this time. The above-described cycle of operations is repeated for each of the remaining pulses. The segment 1424 of the graph in Fig. 14 shows the final potential of the upper terminal of condenser 1014.

The input circuit of tube 1012 is connected to the upper terminal of condenser 1014. Tube 1012 operates as a so-called cathode follower stage and presents such a high impedance to the circuit connected to its input that this tube does not materially affect or alter the potential of the upper terminal of condenser **1014**. However, the cathode of tube **1012** accurately follows or is directly proportional to the potential of the upper terminal of condenser **1014**.

The cathode of tube **1012** is connected to the screen of tube **1013**. The control grid of tube **1013** is coupled to the positive output of the control pulse generator shown in Fig. 8. A positive control pulse will be generated by the control pulse generator in Fig. 8 at the times shown by lines **1404** of Fig. 14 after the upper terminal of condenser **1014** has been discharged to its final value as determined by the received pulses. When this positive control pulse is applied to the grid of tube **1013**, the screen will have supplied thereto a potential determined by the cathode of tube **1012** and thus by the potential of the upper terminal of condenser **1014**. Consequently, a pulse will flow in the output or anode circuit of tube **1013** the magnitude of which is controlled by or dependent upon the potential of the upper terminal of condenser **1014** and thus dependent upon the particular code combination received. If the potential of upper terminal of condenser **1014** has been reduced to a low value, a pulse of low magnitude flows in the output circuit of tube **1013**. If, however, the potential of condenser **1014** has not been reduced to a low value but remains at a relatively high positive value, a pulse of relatively large amplitude will flow in the output circuit of tube **1013**. These output pulses pass through a low-pass filter, represented by a low-pass filter section **1015**. These pulses are then further amplified by tube **1016** and finally pass through a low-pass filter represented by the filter section **1018**.

Low-pass filter **1015** is designed to prevent the transmission of signaling frequencies having a fundamental frequency determined by the frequency of the pulses applied thereto. The low-pass filter section **1018** is designed to prevent the transmission of frequencies above the cut-off of the system, that is, frequencies above the maximum frequency for which the system is designed to transmit. Filters **1015** and **1018** consequently tend to regenerate the complex wave or its image at the receiving station. The regenerated complex wave is then transmitted from the low-pass filter **1018** through the terminal equipment **1019** to a receiving instrument **1020**.

As in the case of the terminal equipment **421** at the transmitting station, terminal equipment **1019** at the receiving station may include any or all of the types equipment mentioned with respect to terminal equipment **421** at the transmitting station. As will be apparent to persons skilled in the art, the terminal equipments at the two ends of the system may include different apparatus and systems, or they may be similar or even identical under some circumstances. In each and all of these cases the terminal equipment and the receiving devices associated therewith operate in their normal manner.

It should be noted that the code combinations which represent large amplitudes of the samples in the transmitting station will cause condenser **1014** to become discharged the most, whereas the code combinations which represent samples of small amplitudes at the transmitting station will cause condenser **1014** to become discharged the least. Inasmuch as the potential of the upper terminal of condenser **1014** determines the magnitude of the pulses transmitted by tube **1013**, it is apparent that the magnitude of the

pulses transmitted by tube **1013** is just the inverse of the magnitude of the samples at the transmitting station. When the pulses transmitted by tube **1013** are amplified and inverted by the right-hand section of the tube **1016**, they will correspond in amplitude to the magnitude of the samples of the complex wave at the receiving station. These pulses may then be transmitted through filter network **1018** or further amplified by additional tubes such as the right-hand section of tube **1016** without further affecting the character of the reconstructed wave or intelligibility of the speech if the complex wave is a speech wave.

Of course, the inverted pulses could equally well be transmitted to the low-pass filter **1018** and reconstruct a complex wave which would be just the inverse of the complex wave at the transmitting station. Such an inverse wave will be equally intelligible and indistinguishable from the original complex wave if they represented speech waves.

Curve **1451** of Fig. 14 represents the wave reconstructed at the receiving station. The heavy dots represent the points determined by the code combinations of pulses transmitted for each sample of the wave **1301** at the transmitter. Point **1453** is the point corresponding to the point **1303** for which the detailed operation of the coding and decoding process has been traced in the preceding description. It will be noted that the form of the wave **1451** differs slightly from that of the wave **1301**. This is due to the quantizing effect of the system; i. e. the amplitude is represented by finite steps rather than by a continuously varying function.

In addition to the receiving equipment shown in Fig. 10 and described above, additional receiving equipment is shown in the lower portion of Fig. 9. The mode of operation of the equipment shown in the lower portion of Fig. 9 varies somewhat from the method described above with reference to the operation of the circuits shown in Fig. 10. In Fig. 9 the output of the coupling and amplifier tube **910** is coupled to the control grid of tube **913**. The screen grid of tube **913** is connected to the output of the exponential wave generating equipment, so that the potential upon the screen grid follows the curve represented by the graph **1401** of Fig. 14.

Normally, tube **913** is biased so that no current flows in its output or anode circuit. However, when the signaling pulses are applied to the control grid of the tube, current pulses flow in the output circuit of the tube. The magnitude of the pulses flowing in the output circuit is determined by the magnitude of the screen potential of the tube. Consequently even though the signaling pulses are all of the same magnitude as applied to the control grid of this tube, the output pulses will vary in magnitude depending upon the potential applied to the screen of this tube.

When the first signaling pulse is applied to the control grid of tube **913**, the screen potential will be subsequently one-half of the maximum value. Consequently the output pulse will have a magnitude represented by line **1432** of Fig. 14. When the screen has a potential of substantially one-quarter of the maximum value, no signaling pulse is received under the assumed conditions. Consequently no pulse will flow in the output circuit of this tube.

However, under other conditions a pulse may be received at this time in which case the pulse flowing in the output circuit of the tube would be half the magnitude of the previous pulse. Such a pulse is represented by the dotted line 1433.

When the potential of the screen has fallen to one-eighth of its maximum value another signaling pulse will be received. This time the pulse generated in the output circuit of tube 913 will have a value equal to one-fourth of the first pulse. Such a pulse is represented by line 1434 in Fig. 14. Each of the succeeding signaling pulses which are received, cause corresponding current pulses to flow in the output circuit of tube 913, each of which has a magnitude determined by the magnitude of the screen potential of tube 913.

The output circuit of tube 913 is coupled through a low-pass filter represented by the filter section 915 to amplifying tube 916. This tube is in turn coupled to amplifying tube 917. Tubes 916 and 917 amplify pulses from tube 913 and repeat them to the low-pass filter represented by the filter section 918.

The effect of the filter sections 915 and 918 is to reconstruct a complex wave from the series of pulses of varying amplitude transmitted through them. The complex wave reconstructed by these filter sections will be similar in wave form to the complex wave sampled at the transmitting station.

It will be readily apparent to persons skilled in the art that the filter sections 915 and 918 may be combined into a single filter and located in either of the positions shown for the sections 915 or 918. Filter section 915 is designed to have a cut-off frequency somewhat below the frequency of the received pulses while filter section 918 is designed to have a cut-off frequency only slightly above the highest frequency which it is desired to transmit over the system. Under the assumed set of conditions where the sampling rate is 8,000 cycles per second and the pulse rate is five or six times that frequency, filter 915 may in a representative system have a cut-off of about 8,000 cycles while the cut-off frequency of the filter 918 should be about 3,000 cycles.

The filters 915 and 918 correspond in function to the filter sections 1015 and 1018, shown in Fig. 10 and may have similar transmission characteristics and cut-off frequencies. However, the filters or filter sections shown in Fig. 10 may have any suitable type of termination or terminating sections, whereas in the system shown in Fig. 9 it is desirable that the filter sections 915 and 918 have a mid-shunt termination connected to the output of the respective tubes which are preferably of the pentode or constant current output type of tube.

From the filter section 918 the reconstructed wave is transmitted through the terminal equipment 919 to the receiving device 920. Terminal equipment 919 and receiving device 920 may be similar to the terminal equipment 1019 and receiving device 1020 or the terminal equipment 919 and receiving device 920 may include any of the types of equipment mentioned above with reference to the terminal equipment and receiving devices mentioned with reference to a description of Figs. 1 and 2.

Either one of the receiving devices shown in Figs. 9 and 10 may be used as the normal receiving equipment and the other device as the monitoring equipment. Furthermore, as pointed out above, the operation of either of the devices may be disabled by opening the respective switches 928 or 929.

The monitoring equipment shown in Fig. 6 at the transmitter station is similar to the receiving equipment shown in Fig. 10 and operates in the same manner as the equipment shown in Fig. 10 and described with reference thereto. However, it will be obvious that the receiving equipment shown in the lower portion of Fig. 9 could be used equally well for the monitoring equipment at the transmitting station and could replace the monitoring equipment shown in Fig. 6 without change. In this case it would operate in the same manner as described above with reference to the equipment shown in the lower half of Fig. 9.

It should be noted that a series of five permutation code pulses is generated for each sample of the complex wave at the transmitting station and that these permutation code pulses are of one of either of two different signaling conditions. At the receiving station the code pulses are decoded to again form pulses of varying amplitude from which a complex wave similar to the complex wave at the transmitting station is reconstructed.

It should be further noted that no pulse is normally transmitted immediately following the generation of the control or synchronizing pulses 1305 and 1405 unless the system is overloaded or operated in some other improper manner. The pulse position immediately following the synchronizing or control pulses 1305 and 1405 has been left blank so that if desired synchronizing pulses may be transmitted during this time interval and employed at the receiving station to maintain the equipment there in synchronism with the received signals. In this case it will not be necessary to provide a separate synchronizing path or channel 580. However, inasmuch as equipment of this type will operate in its usual manner when cooperating with the system disclosed herein, the present description of a typical system employing the present invention has not been burdened with or expanded to include a detailed description of apparatus of this type. Instead, a simple additional synchronizing channel 580 has been shown. It will be obvious to persons skilled in the art that in so far as coding and decoding apparatus is concerned, the operation will be substantially the same so long as equipment is maintained in synchronism at the two ends.

It should be pointed out however that with continuously varying exponential wave forms at the two ends of the system, it is not essential that these wave forms be maintained in absolute synchronism with the received signals because of the characteristic of a continuously varying exponential wave which is that the change in the magnitude of the wave is the same fraction thereof during any given interval of time. Thus, if the two waves are not in the same relative phase with respect to the transmitted permutation code signals at the two ends of the system, the only result will be that the absolute magnitudes of the complex waves at the two ends of the system will not be equal. Instead they will be directly proportioned. In other words, a slight variation in the synchronism of the equipment in the two ends of the system will result in a variation of the gain or loss of the system. It is only necessary that all of the permutation code pulses of each code combination are affected or compared with a given exponential wave.

What is claimed is:

1. In a communication system, apparatus controlled by the instantaneous amplitude of a complex wave for obtaining samples thereof at rapidly recurring instants of time, means for determining the magnitude of each of said samples comprising a standard of comparison which continuously and exponentially varies with time, means for comparing said standard with said sample, apparatus for transmitting a pulse at recurring instants of time when said sample exceeds said standard of comparison at said instants of time and apparatus operative incident to the transmission of each of said pulses for reducing the magnitude of said sample by the amount represented by said pulse.

2. In a communication system, apparatus controlled by the instaneous amplitude of a complex wave for obtaining samples thereof at rapidly recurring instants of time, means for determining the magnitude of each of said samples comprising a standard of comparison which continuously and exponentially varies with time, means for comparing said standard with said sample, apparatus for transmitting a pulse at recurring instants of time when said sample exceeds said standard of comparison at said instants of time and apparatus operative incident to the transmission of each of said pulses for reducing the magnitude of said sample by an amount determined by the magnitude of said standard at the time each of said pulses is transmitted.

3. Apparatus for representing the magnitude of an electrical quantity by means of a series of pulses each of one of two different characteristics, comprising a source supplying a continuously varying exponential wave, apparatus for comparing said wave with said quantity, apparatus for transmitting pulses at predetermined instants of time along said wave and apparatus controlled by said comparing apparatus for determining the character of each of the pulses transmitted.

4. Apparatus for representing the magnitude of an electrical quantity by means of a series of pulses each of one of two different characteristics, comprising a source supplying a continuously varying exponential wave, apparatus for comparing said wave with said quantity, apparatus for transmitting pulses at predetermined instants of time along said wave, apparatus controlled by said comparing apparatus for determining the character of each of the pulses transmitted, and appaartus operative incident to the transmission of pulses of one character for reducing the magnitude of the said quantity by an amount determined by the magnitude of said exponential wave at the time the respective pulse is transmitted.

5. Apparatus for representing the magnitude of an electrical quantity by means of a series of pulses each of one of two different characteristics, comprising a source supplying a continuously varying exponential wave, apparatus for comparing said wave with said quantity, apparatus for transmitting pulses at predetermined instants of time along said wave, apparatus controlled by said comparing apparatus for determining the character of each of the pulses transmitted, apparatus operative incident to the transmission of pulses of one character for reducing the magnitude of the said quantity by an amount determined by the magnitude of said exponential wave at the time the respective pulse is transmitted and apparatus for maintaining the magnitude of said quantity substantially constant during and after transmission of pulses of a different characteristic.

6. In a communication system, apparatus responsive to a series of permutation code pulses each pulse of which may be any one of a plurality of different types, equipment for generating a continuously varying exponential wave for each permutation code series of pulses, equipment for charging a condenser to a predetermined potential for each of said series of permutation code pulses, apparatus jointly responsive to received pulses and to the magnitude of said continuously varying exponential wave for changing the charge on said condenser by progressively smaller amounts for each of the succeeding pulses of one type of each series.

7. In a communication system, apparatus for receiving permutation code series of pulses, each series of which represents the instantaneous amplitude of a complex wave, equipment for decoding each series of said pulses comprising apparatus for generating a continuously varying exponential wave form for each said series of pulses, amplifying apparatus for amplifying each of the pulses of each of said series of pulses, equipment responsive to said continuously varying exponential wave for continuously changing the amplification of said amplifying apparatus so that each of the pulses of each series is amplified less than the previous pulse of said series.

8. In a communication system, apparatus for receiving permutation code series of pulses, each series of which represents the instantaneous amplitude of a complex wave, equipment for decoding each series of said pulses comprising apparatus for generating a continuously varying exponential wave form for each said series of pulses, amplifying apparatus for amplifying each of the pulses of each of said series of pulses, equipment controlled by said continuously varying exponential wave for continuously changing the amplification of said amplifying apparatus so that each of the pulses of each series is amplified less than the previous pulse of said series, apparatus responsive to said variously amplified pulses for reconstructing the complex wave form therefrom.

9. Apparatus for generating a plurality of series of permutation code pulses each series of which represents a magnitude which comprises apparatus for generating a continuously varying exponential wave for each magnitude, apparatus for adding said wave to said magnitude, equipment for reducing said magnitude at predetermined intervals of time when said sum exceeds a predetermined quantity and apparatus operative incident to each reduction of said magnitude for transmitting a pulse of a predetermined character.

10. In a communication system for the transmission of complex wave forms representing information, apparatus for sampling the instantaneous amplitude of said wave form at predetermined intervals of time, equipment for generating a continuously varying exponential wave for each of said samples, means for adding together the magnitude of said sample and the exponential wave individual thereto, apparatus operative at predetermined instants of time during said wave for reducing the magnitude of said sample when said sum exceeds the predetermined

quantity, other apparatus operative incident to the reduction of said sample for the transmission of a pulse of a predetermined character, equipment responsive to said pulses, other equipment for generating another exponential wave for each series of said pulses, apparatus for varying the magnitude of each of the pulses of a given series and equipment for reconstructing a complex wave from said pulses of varying magnitude.

11. In a communication system, a condenser, apparatus for storing charges of varying magnitude upon said condenser, means for generating a continuously varying exponential wave for each charge stored upon said condenser, apparatus for adding said exponential wave to the potential of said charge, an electric conduction device having a plurality of control elements for discharging said condenser, timing apparatus connected to one of said control elements for determining the times of discharge of said condenser, means for supplying the continuously varying exponential wave to a control element of said device for determining the amount of discharge of said condenser and an element of said device controlled by said sum for selectively determining at which of said times said condenser will be discharged.

12. In a communication system, a condenser, equipment for charging said condenser to different potential values, an exponential wave generating device for generating an exponential wave for each charge applied to said condenser, a pentode vacuum tube for discharging said condenser, an impulse timing circuit connected to one of the grids of said pentode, another of the grids of said pentode being connected to said exponential wave generator, equipment for adding said exponential wave to the potentials of said charges upon said condenser, a third grid of said pentode controlled by the sum of said exponential wave and said charge for selectively determining the instants during which said condenser is discharged and equipment operative incident to each discharge of said condenser for transmitting a pulse of constant amplitude and constant duration.

13. In a communication system, means for recurrently sampling a wave to be transmitted to produce a first electrical quantity proportional to each sample, means for producing for each of said first quantities a second electrical quantity continuously varying at an exponential rate for a predetermined period, means for comparing each of said first electrical quantities with the corresponding second electrical quantity, repeatedly during said predetermined period, means responsive to each operation of the comparing means for transmitting a pulse of one characteristic when said first quantity is greater than said second quantity and of a second characteristic when said second quantity is greater than said first quantity, and means responsive to the comparing means when said first electrical quantity is the greater for reducing said first quantity by an amount proportional to the value of said second quantity at the time of comparison.

WILLIAM M. GOODALL.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,048,081	Riggs	July 21, 1936
2,401,447	Wipff	June 4, 1946