

# WIDELY SEPARATED CLOCKS WITH MICROSECOND SYNCHRONIZATION AND INDEPENDENT DISTRIBUTION SYSTEMS

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## Summary

In a majority of timing applications, a problem exists in setting two or more clocks to agree with one another. Present techniques using WWV or other high frequency broadcasts allow clocks to be synchronized within one millisecond. This paper describes a method which offers an improvement in synchronization of three orders of magnitude.

Microsecond synchronization is obtained by use of the Loran-C navigation system as the link between a master clock at Boulder, Colorado and any slaved clock anywhere in the Loran-C service area.

The timing system also includes a unique method for distribution of several time code formats on a single UHF channel.

## Introduction

Three solutions to the problem of time synchronization of widely separated clocks have been proposed by Morgan [1]. These methods are:

- (a) Transportation of a master clock to each location where synchronization is desired,
- (b) two-way transmission of radio signals between a master clock and the slave clock, and
- (c) one-way transmission of radio signals from a master clock to a slave clock.

The timing system which is described here uses one-way transmission of LF radio signals (method c) to synchronize a slave clock to a master clock and one-way transmission of UHF radio signals to distribute time to the user from the slave clock.

The WWV transmissions are perhaps the most widely known and for many applications the most useful broadcasts. The equipment required is both inexpensive and readily available. Their major disadvantage is in the accuracy of time synchronization available. While millisecond time is accurate enough for many applications, modern scientific measurements require at least one or two and often three orders of magnitude better than this. For this reason, several studies have been made on the stability of signals at LF and VLF [2, 3, 4, 5]. As a result of these and other studies, several systems have been proposed which would supply standard frequency and time on a world wide basis. One of these, Loran-C, is already in operation as a precise 100 kc navigation system [6]. The operation of Loran-C is such that when synchronized to a time and frequency standard, microsecond synchronization is available anywhere within the service area of the system [7].

Once a clock has been synchronized with the master clock, the time information must be distributed to the user. In order to cover the wider range of recorder applications, serial time codes are generated at rates from one ppm to 1000 pps. All these codes are time-division multiplexed on a single UHF channel for distribution to the user. This equipment will be described after the clock and its synchronization have been discussed.

## I. MICROSECOND SYNCHRONIZATION

### The Loran-C Navigation System

The Loran-C navigation system is a precise 100 kc pulse system which obtains its accuracy by means of pulse sampling. Figure 1 shows the manner in which this sampling is accomplished. A signal reflected from the ionosphere will arrive at the receiver with a random phase relationship some time after the direct or ground wave signal. A gate samples the signal ahead of the arrival of the sky wave so that only the ground wave is used to synchronize the system. The propagation time of the ground wave can be calculated to one microsecond over a land path and to one-tenth of a microsecond over a sea-water path.

IRE WESCON Record, 1960.

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The system consists of at least three stations, a master and two or more slaves. On the East Coast Chain, the slave stations are located at Jupiter Inlet, Florida and Martha's Vineyard, Massachusetts. The master station is located at Cape Fear, North Carolina. When used as a navigation system, a hyperbolic line-of-position is determined by the master station and each of the slaves. The intersection of these lines-of-position (LOP's) gives the location of the receiver to better than 1000 feet at ranges of 1000 miles over sea water and land.

The National Bureau of Standards is proposing to synchronize the Loran-C system, which is operated by the U. S. Coast Guard, with the United States Frequency Standard (USFS) at Boulder, Colorado [8]. Signals from the Loran-C station at Cape Fear will be monitored and compared against the USFS. Corrections will be made to the master oscillator at Cape Fear to keep the synchronization well within a microsecond of the USFS. Another more refined and more expensive plan proposes the establishment of a Loran-C station between Cape Fear and Boulder. This plan has two very definite advantages. First, the East Coast Chain would be expanded to a star, providing navigation coverage of the Great Lakes and the Gulf of Mexico. Second, very good ground wave signals would be available at Boulder. This star chain plus a station located in the southwestern United States would provide Loran-C coverage for the entire continental United States. The entire system could be easily monitored at Boulder.

#### A Loran-C Clock

In order to fully utilize the capabilities of the Loran-C system for timing, a clock of some type is required. This clock must be capable of resolving time to one microsecond, it must be capable of being easily synchronized by the Loran-C signals, and the time in the clock must be in a format that can be used external to the clock. Such a clock has been constructed at the Boulder Laboratories of the National Bureau of Standards. Figure 2 shows the manner in which this clock is constructed. The Loran-C receiver fits in the space on the right. The space on the left is occupied by the clock. A visual readout is visible directly above the monitor oscilloscope in the center section.

#### Clock Divider

The clock divider consists of 15 trochoidal beam-switching tubes operating as decimal counters. These tubes are arranged so that the first operates at one megacycle, the second at 100 kc, and so on to the 15th which operates every 100 days.

Figure 3 shows a typical divider stage. The carry output for the previous stage is produced by gating the input pulse rate with the number

nine output from the previous beam-switching tube. This method reduces the carry propagation time through the divider to less than one microsecond. The carry output is used to trigger a bistable multivibrator which drives the beam-switching tube. An additional input to the bistable multivibrator allows counts to be added to each decade as an aid to synchronizing the clock.

The first counter is driven directly by the megacycle pulses from the pulse generator and no gating is involved. The seconds and minutes counters are arranged to reset to zero by themselves on their 60th count. The hours counters are reset automatically to zero on their 24th count. The days counters are allowed to count to 399 before they reset. This requires a manual clock reset once a year.

#### Readout Register and Display

The readout register must, upon command, store and display the time of the command. The manner in which this is accomplished is demonstrated in Figure 4. Since the read command can occur randomly, it is used to select one of the microsecond pulses. This pulse is then delayed less than a microsecond to insure that all the beam switching tubes are in a stable state. Each output from the beam-switching tubes is connected to one input of an "and" gate. The delayed read command is connected to the other gate input and to the reset input of a bistable multivibrator. The gate output triggers a monostable multivibrator. The pulse from the monostable multivibrator trailing edge is fed to the set input of the bistable. Thus, ten bistable multivibrators will store the number in the decade until the next read command. The time between successive read commands must be sufficient to allow the monostable multivibrators to recover. The prototype requires 200 microseconds to recover. This means the read commands cannot occur closer together than 400 microseconds.

Two types of display are available. The output from the bistable is permanently connected to an incandescent display. This readout is always visible to the operator and is required to synchronize the clock. Also available is a high speed photographic readout. The output from the monostable multivibrator flashes a "nixie" indicator tube for 200 microseconds. This readout is useful for rapidly recording the time of a discrete event to the nearest microsecond.

#### Synchronization of the Clock

The Loran-C receiver provides two types of information to the clock, both of which must be used to obtain the desired microsecond synchronization. This information is derived from the 100 kc carrier and from the pulse rate which is transmitted.

Frequency Synchronization. Before any thought can be given to synchronizing a clock in time, a stable and accurate frequency source must be available. Figure 5 shows the manner in which this frequency is derived from the Loran-C receiver. The local oscillator supplies 500 kc to two phase shifters. The number one shifter is driven directly from a servo motor and number two is driven by the same motor through a clutch. The output from the first phase shifter is divided by five to supply the local 100 kc signal for the Loran-C receiver. The output from the second phase shifter is used to generate pulses at a megacycle rate for the clock. The clutch output also drives an integral control unit which adjusts the frequency of the oscillator. If the Loran-C receiver loses synchronization with the transmitter, the clutch is disengaged and the oscillator is allowed to free run. The clock accuracy, until synchronization is re-established, then depends upon the stability of the local oscillator.

Time Synchronization. Loran-C is not presently instrumented to resolve time increments larger than 50 milliseconds. However, identification of one second increment could be instrumented without affecting the navigation accuracy. Increments of time not resolved by Loran-C can easily be resolved by WWV.

Loran-C pulses are broadcast in groups of eight with a group repetition rate (GRR) of twenty per second. The first pulse in one of these groups of eight occurs exactly on the second at the master transmitter. Figure 6 shows some of these pulse groups and their relation to the pulse transmitted by WWV for a hypothetical site.

WWV must be used to set the correct time into the clock down to 50 milliseconds. It may be used below this, but is not necessary. Loran-C is now used to set the clock correct to the nearest microsecond. In order to demonstrate the technique used, the following example is given:

Assume, first, a location 1000 miles from a slave transmitter with an all sea water propagation path; and second, a Loran-C receiver with an instrumentation delay of 25 microseconds.

This information is now used to calculate the total delay from the master transmitter to the GRR output of the receiver.

<sup>1</sup> Based on the East Coast Chain. Fractional repetition rates can be handled by modified instrumentation techniques.

Propagation time-master to slave:

	2711.8 $\mu$ sec
Slave coding delay:	12000.0 $\mu$ sec
Propagation time-1000 mi of sea water:	
	5373.1 $\mu$ sec
Receiver delay:	25.0 $\mu$ sec
	<hr/>
Total delay:	20109.9 $\mu$ sec

Figure 6 shows the manner in which these delays are related.

At any time after the second, the first six counters will have advanced some number of microseconds. This number may be read out and displayed by commanding the readout storage register. When this read command is derived from the Loran-C receiver as shown in Figure 6, the number of microseconds will be 20110. This is the sum of all propagation and instrumentation delays from the master transmitter to the receiver output.

If the readout register does not display this number of microseconds, that is, if the second pulse in the clock does not coincide with the second pulse at the master transmitter, then the counters are adjusted until this number is displayed. Once the microsecond counters have been set and the counters from seconds to days have been set using WWV, no further adjustments need be made. Since the oscillator is phase-locked to the one at the master transmitter, any tendency to drift is immediately corrected.

This completes the discussion of the clock and the methods for microsecond synchronization. Since microsecond time alone is not sufficient for this application, serial time codes are generated for recorders. The generation and distribution of these codes will now be discussed.

## II. DISTRIBUTION OF MICROSECOND TIME

### Generation and Distribution of Time Codes

Most timing distribution systems in current usage generate all required codes at a central location then distribute each code separately to the user. Therefore, a terminal site may have several channels carrying time information to it. In the system to be described, the single channel is an integral portion of the time code generator. That is, the code is not generated on time until the required information reaches the terminal site. The system can be described in three sections:

- (1) The encoder, which receives time information from the clock and supplies code information to the link,
- (2) The link, a UHF transmitter and receiver, and

(3) the decoder, which takes the coded information from the link and generates the necessary time codes.

### The Encoder

The encoder takes time information from the clock in decimal form and encodes it in such a manner that all the information can be transmitted on a single channel. The information which is included in the prototype system includes four proposed time codes for the Inter-Range Instrumentation Group (IRIG) combination code, five time codes for the Atlantic Missile Range (AMR), and one countdown, or "T"-time, code. The IRIG codes include both binary-coded-decimal (BCD) and straight, or pure, binary (SB). The AMR codes are coded binary (CB).

The encoder may be further divided into several subsections. These are the time generator, the rate generator, the code generators, and the code multiplexer.

The Time Generator. The time generator receives 10-line decimal time from the clock and produces three binary time format outputs. Ten decimal-to-BCD conversion matrices produce the BCD output in a 4-line format from tenth of seconds to hundreds of days. The coded binary time is produced by three registers of bistable multivibrators. The first register counts seconds up to 59 when it is reset by a pulse from the clock. This register produces a 6-line output for seconds. A second register counts minutes up to 59 when it is reset by a pulse from the clock. Again a 6-line output is generated for minutes. Finally, a register counts hours up to 23 when a clock pulse resets it. A 5-line output is generated. In order to generate the time of day in straight binary seconds, a register of 17 bistable multivibrators are used. This register counts seconds from the clock and is reset once a day by a pulse from the clock.

Rate Derivation and Format. In order to send 10 time codes over a single-channel information link, some method of multiplexing the code information is required. Such a scheme, employing time-division multiplexing, is shown in Figure 7.

Because the fastest code rate to be transmitted is 1000 pps, this rate was selected as a basic rate for the system. The information to be transmitted is always contained within a 1000 microsecond sync interval. In order to position the information properly in the interval, the encoder must sample the time one millisecond early, then delay the information to the proper

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This SB register is not included in the prototype equipment but the CB registers may be rewired to provide SB time.

position in the sync interval. The receiver then selects the information from the sync interval and uses the following 1000 pps sync pulse to generate the time codes. An additional 30 microseconds of time advance are introduced so that the propagation time may automatically be corrected within six miles of the transmitter.

The codes and rates which are derived are:

<u>IRIG Codes</u>	<u>AMR Codes</u>	<u>Rates</u>
1 ppm	1 ppm	1 ppm
2 pps	1 pps	1 pps
	20 pps	2 pps
100 pps	100 pps	20 pps
	500 pps	100 pps
1000 pps		500 pps
		1000 pps

A total of nine code formats at seven rates result. An additional rate of 20 kpps is derived and is used to correctly position the pulses in the sync interval. The technique used to derive these rates is shown in Figure 8. A 100 kpps rate is gated to derive a 20 kpps rate which is 30 microseconds early. This rate is then gated down to 1000 pps, also 30 microseconds early. All rates following are derived from the 1000 pps gate 1030 microseconds early.

Code Generators. The code generators must use the desired rates to generate a signal which is multiplexed into the sync interval. Two methods are available to perform this generation, one conventional and one not so conventional.

The conventional method uses two parallel registers and produces a serial output. One register counts time and is transferred into the second, which is a shift register. The information is shifted out of the register and generates a time code at the output. In the second, and unconventional method which is used in this encoder, prior knowledge is used to sample time information stored in a register. Figures 9 and 10 demonstrate the required information and how it is used.

In order to determine the proper place in the sync format at which a particular point in the time register must be sampled, the time code must be inspected. Figure 9 shows the first portion of a proposed IRIG 100 pps code. Because the time code is desired at the correct time at the terminal equipment, advance sampling of 1030 microseconds is used at the transmitter.

For example, in order for the 10 second bit to occur at the terminal equipment exactly on index count number six, the 10 second BCD output must be sampled during the index interval beginning on count five. Since, for this code, index count five always corresponds to a time 50 milliseconds after the second, outputs from the beam-

switching tubes in the divider are used to select this interval for sampling. Figure 10 shows the logical "and" gate used to sample this time while Figure 11 shows a timing diagram of the sampling operation. In order to avoid ambiguity between 50 milliseconds and 150 or 250 milliseconds, the zero output from the tenth second counter (marked as 000 milliseconds) is used along with the number five output of the ten millisecond counter (marked as 50 milliseconds). This sampling technique is used for each information bit in this code.

This method will obviously only generate a "one" for the time bits. Some simple method must be devised to generate "zeros" for the time bits and for all other index counts except the reference marks as well as to generate the reference marks. Figure 10 also shows the method used to generate a "zero" unless a "one" or a "mark" is to be generated. The rate, in this case 100 pps, is used to set a bistable multivibrator whose output feeds a 3-input and gate. This bistable multivibrator is reset after two milliseconds. The other two gate inputs are inhibited by other bistable multivibrators, one for the "one" code and one for the "mark". If neither bistable multivibrator is set by a "one" or a "mark" pulse, then the output of the "zero" bistable multivibrator appears at the code output. If either the "one" or "mark" bistable multivibrator is set, the "zero" output is inhibited. The "one" and "mark" are mutually exclusive as is seen from the code format.

The reset pulses for the bistable multivibrators are derived from the clock divider. The "mark" set pulses are derived in the same manner as the "one" pulses, except a 3-input and gate is used<sup>3</sup>.

Code Multiplexer. The code multiplexer takes the information from the nine code generators (four IRIG, five AMR) and multiplexes it onto a single channel for broadcast over the UHF link. Figure 12 shows a portion of the multiplexer which demonstrates how this is accomplished.

The 1000 pps rate, which synchronizes the receiver, is fed directly to the code multiplexer output. The inputs from the code generators must each be delayed to its unique position in the sync interval. The information which is actually broadcast consists of set and reset pulses. This information is derived from the rate and length of the code generator output pulse. Since all codes of the same rate, regardless of format, turn on at the same time, each rate is delayed to its correct position in the sync interval and transmitted. The 20 kpps rate is used as a reference to correctly position the pulse exactly on a 50 microsecond mark in the interval. This is demonstrated for the 100 pps rate in Figure 12.

<sup>3</sup>Special techniques are used on the 500 and 1000 pps codes.

In order to generate the reset pulse for the code, the output of the code generator is differentiated to initiate its delay. Again, the 20 kpps rate is used to re-establish the system accuracy. This procedure is repeated for each rate and code.

It should be noted that the relative position of the pulses within the sync interval is immaterial. Because of the system logic the set pulse will always occur in an interval which precedes the reset pulse. However, because of some simplifications made in the demodulator, the 100 pps reset pulses should appear as shown in Figure 7. This will be discussed shortly.

#### The Information Link

The link must transmit the information from the output of the encoder to the input of the decoder. A UHF distribution system is employed in the prototype system. This includes a single transmitter at a central location and a receiver at each recording site.

The Transmitter. The transmitter which is used in this system is a simple pulsed cavity oscillator. A blocking oscillator is used to pulse the cavity which operates at a frequency of 1.75 Gc<sup>4</sup>. A coaxial transmitting antenna is mounted at a height above nearby obstacles.

The Receiver. The receiving antenna is a dipole mounted in a corner reflector or horn. The antenna feeds a crystal mixer. The local oscillator is another cavity oscillator which operates continuously. A 60 Mc IF strip provides the required gain. The detected output from the IF strip is fed directly to the input of the decoder.

Using this relatively simple system, signals were received at a range of 40 miles with a signal-to-noise ratio of 20 db.

#### The Decoder

The decoder must take the output from the receiver, separate the sync pulses, examine the sync interval for information, and generate the time codes. Two units are used to perform these functions, a sync interval demodulator, which separates the sync pulses from the rest of the information and generates a ramp output, and a time code demodulator, which uses the ramp and sync pulses to examine the sync interval for information to generate a time code and rate output.

The Sync Interval Demodulator. The sync interval demodulator is required at every site in order to separate the 1000 pps sync pulses and to generate the ramp which is required

<sup>4</sup>Gc = Gigacycles = 10<sup>9</sup> cps.

for the code demodulator.

The broadcast code format is such that the last 100 microseconds of the sync interval are always vacant and alternate sync intervals are usually vacant (Figures 7 and 14). These empty spaces are used to simplify the synchronization of the demodulator. The manner in which the sync demodulator operates is shown in Figures 13 and 14. The first pulse, no matter when it occurs, passes through an "and" gate and triggers a bootstrap ramp generator. The bootstrap inhibits the gate for the length of the ramp, 900 microseconds. After the bootstrap has removed the gate inhibition, the next pulse is allowed through to repeat the cycle. If the first pulse occurred in the middle of some particular sync interval, then the ramp will turn off in the middle of the following interval, which will probably be empty. Figure 14 shows how the unsynchronized ramp would be synchronized by the IF output using the sync pulses and empty intervals.

The outputs which are produced by the sync interval demodulator are: First, the ramp, which is used to generate the delays required for the code demodulator; second, the sync pulses, which are used to synchronize the various time codes within a microsecond; third, a clamp output, which is used to discharge capacitors for high speed operation; and fourth, a test pulse, which would be used as an aid for tests and alignment. This test pulse is derived in exactly the same manner as the rate, or synchronized set, pulses in the code demodulator and is usually adjusted for a one pps output.

Time Code and Rate Demodulator. The code demodulator must take the outputs from the sync demodulator and use them, along with the IF output, to generate the desired time code. One such demodulator is required for each code output desired. Figures 15 and 16 describe the operation of a typical demodulator<sup>5</sup>.

The ramp output from the sync demodulator is used with a delay pickoff to select a portion of the sync interval to be examined. The portion of the interval which is examined is different for each code. Because of the manner in which the codes are generated in the encoder, the set pulse will occur in an interval which is several milliseconds ahead of the interval containing the reset pulse. Therefore, the relative position of the set and reset pulses in the sync interval is arbitrary. When a set pulse occurs in the interval at the point where the delay pickoff is sampling, a gate is opened which allows the next sync pulse to set a bistable multivibrator. This is the bistable multivibrator which produces

the code output. This synchronized pulse occurs at the code rate, correct in time, and is brought out separately as a repetition rate. When the reset pulse occurs in the interval and is recognized by the delay pickoff, it is used directly to reset the output bistable multivibrator. This means that the reset pulse is not synchronized with the 1000 pps sync rate. The effect of this operation on the code output is negligible. The difference between a pulse 2000 microseconds wide and one 2050 microseconds wide is barely discernable at a 100 pps rate and is even less so at the slower code rates. Since the percentage error is potentially greatest on the 100 pps code, these reset pulses are spaced closest to the front of the interval.

The instrumentation used for the 500 and 1000 pps codes is different partially because of format and partially because of speed. The 500 pps (AMR) code is a presence-absence code which is sent for only 38 milliseconds each second. The 1000 pps (IRIG) code occurs at the same speed as the sync pulses. Instead of using separate set and reset pulses for these codes, a single pulse technique is used along with monostable multivibrators. Approximately the same technique is used in the 1000 pps demodulator as is used in the code generators to produce a "zero" output unless instructed otherwise. This eliminates the need of sending 1000 pps code information in every interval.

#### Closing Comments

While this system is designed primarily for missile range timing, there are many other applications where timing to the indicated accuracy is desired. Some examples of these applications are:

- (1) The positioning of high altitude aircraft by means of a UHF pulse broadcast from the aircraft and received at several locations against a common time base,
- (2) the location of thunderstorms by precisely fixing lightning discharges,
- (3) the accurate position fixing of nuclear detonations by similar techniques, and
- (4) the precise measurement of time variations on high frequency transmissions such as WWV as an aid to better understanding of propagation phenomena.

The distribution of accurate time in large metropolitan areas can be accomplished by use of the system described, but using a television station for the link. In this manner, one centrally located clock could supply microsecond time to an entire metropolitan area such as Los Angeles.

During the summer of 1960, the system was completed by the National Bureau of Standards,

<sup>5</sup>

All the demodulators are identical except for the 500 and 1000 pps codes.

Boulder Laboratories, Central Radio Propagation Laboratory, Navigation Systems Section. Except for the beam-switching tubes in the divider, the UHF transmitter and receiver, and portions of the Loran-C receivers, solid state circuitry is used throughout.

GLOSSARY

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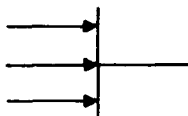
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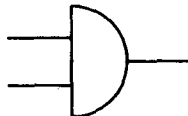
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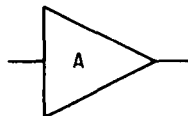
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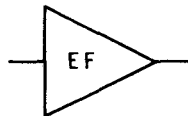
Logical "or" Circuit



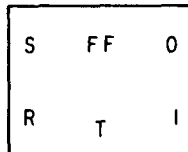
Logical "and" Circuit



Amplifier (no inversion)

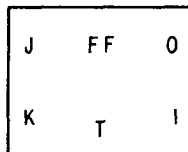


Emitter Follower



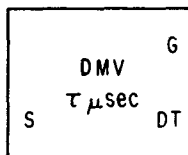
Bistable Multivibrator (flip-flop)

S = set input  
R = reset input } cannot be used together  
T = toggle input  
(for symmetrical triggering)  
O = output after reset  
I = output after set



Bistable Multivibrator (flip-flop)

J = set input  
K = reset input } can be used together



Monostable Multivibrator (one-shot or delay multivibrator)

S = set input  
G = gate output  
DT = delayed trigger output  
 $\tau$  = duration of delay

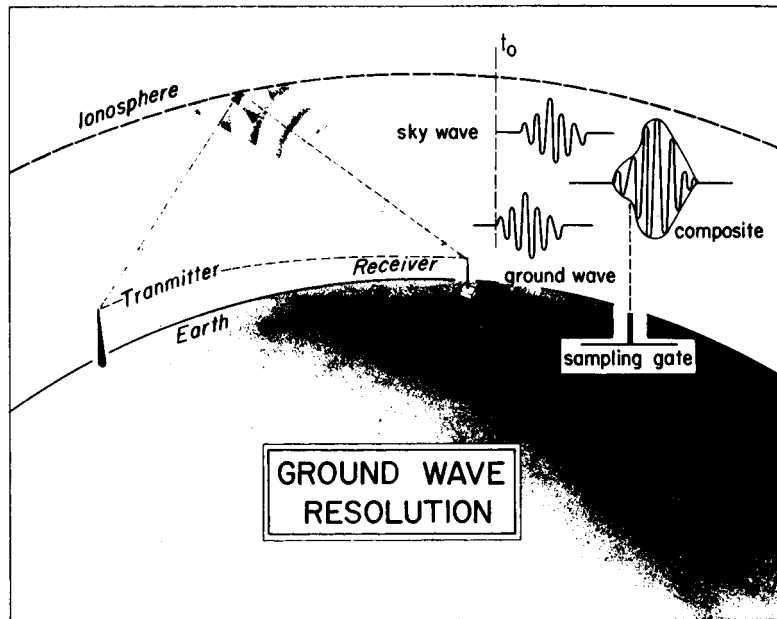


Fig. 1. Ground wave resolution.

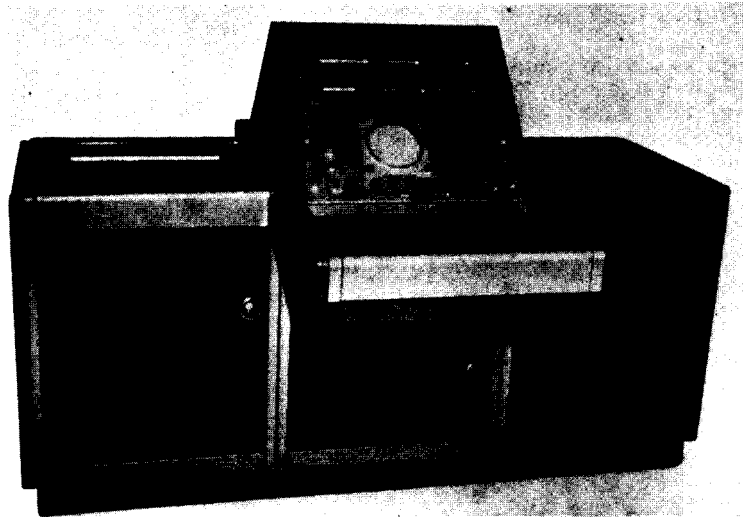


Fig. 2. A Loran-C clock.



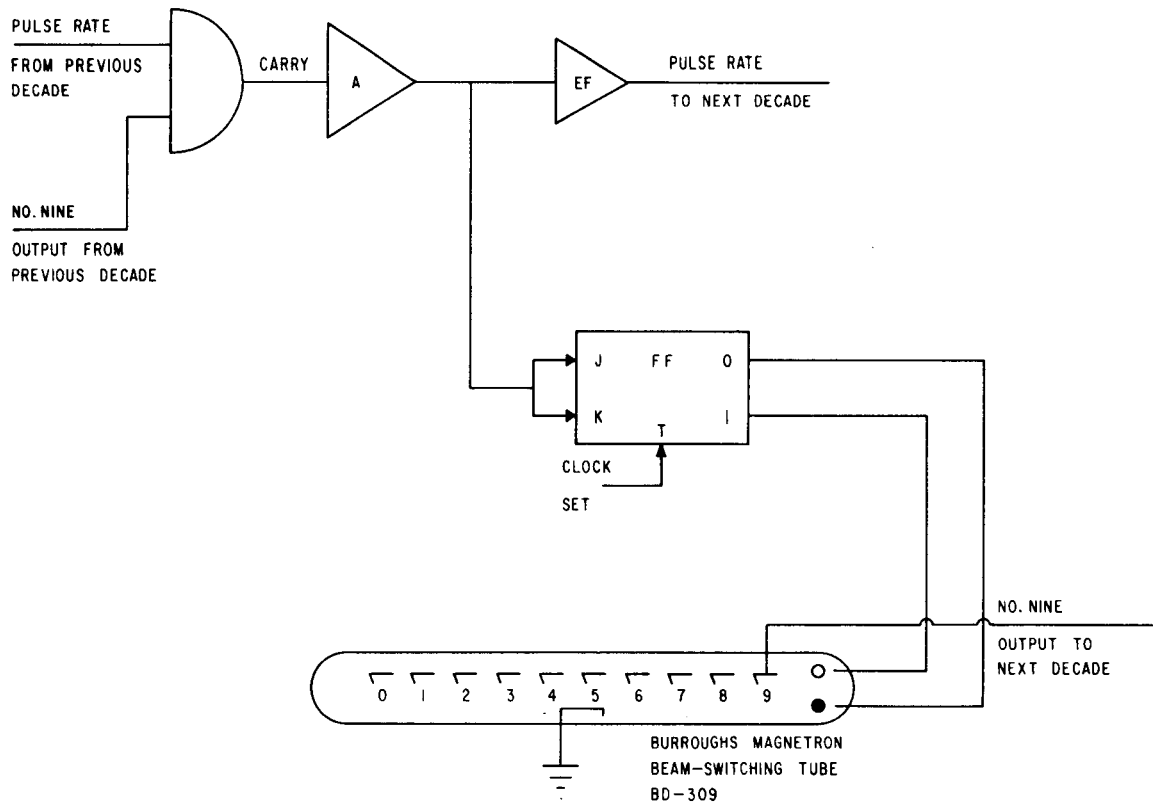


Fig. 3. Typical divider decade.

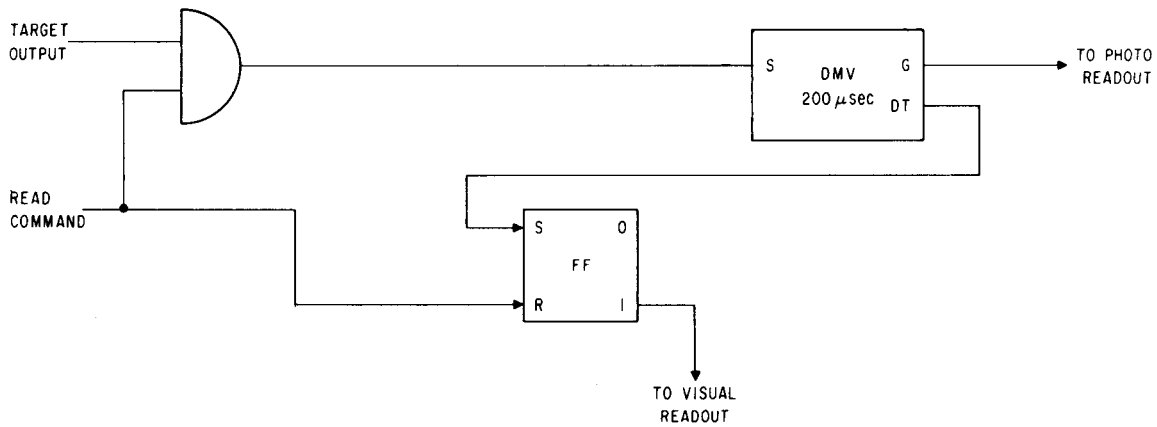


Fig. 4. Readout logic diagram.

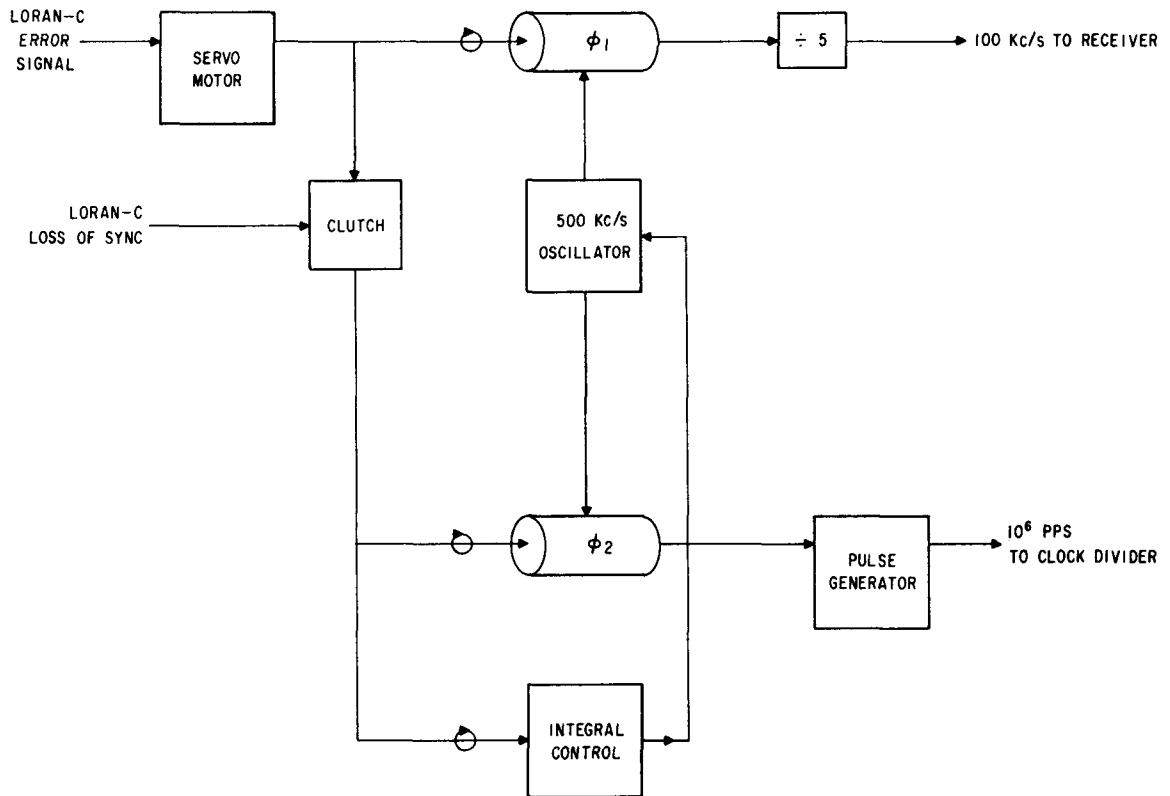


Fig. 5. Frequency control.

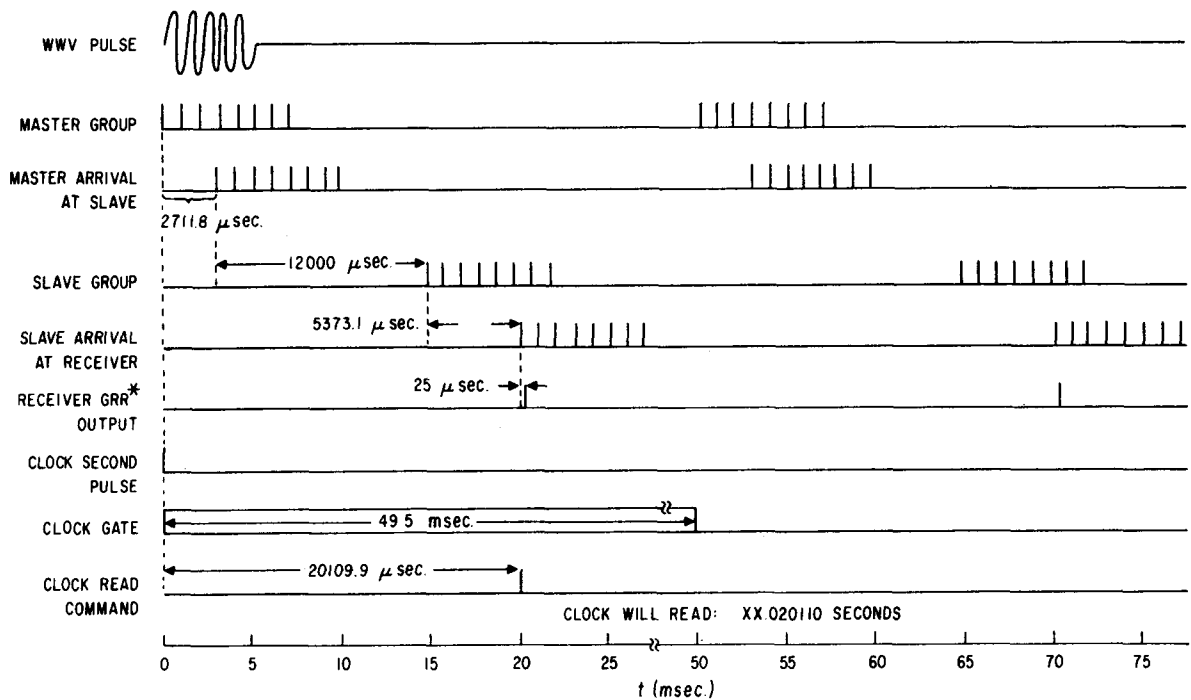


Fig. 6. Example of the time relationship for WWV and Loran-C pulses.

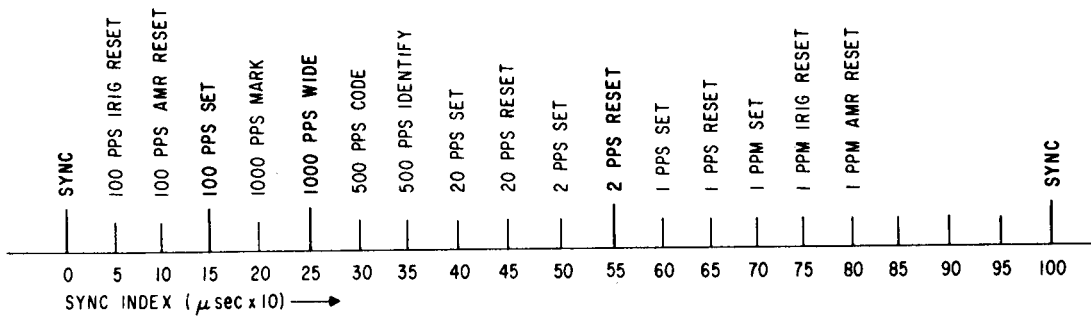


Fig. 7. Synchronizing interval format.

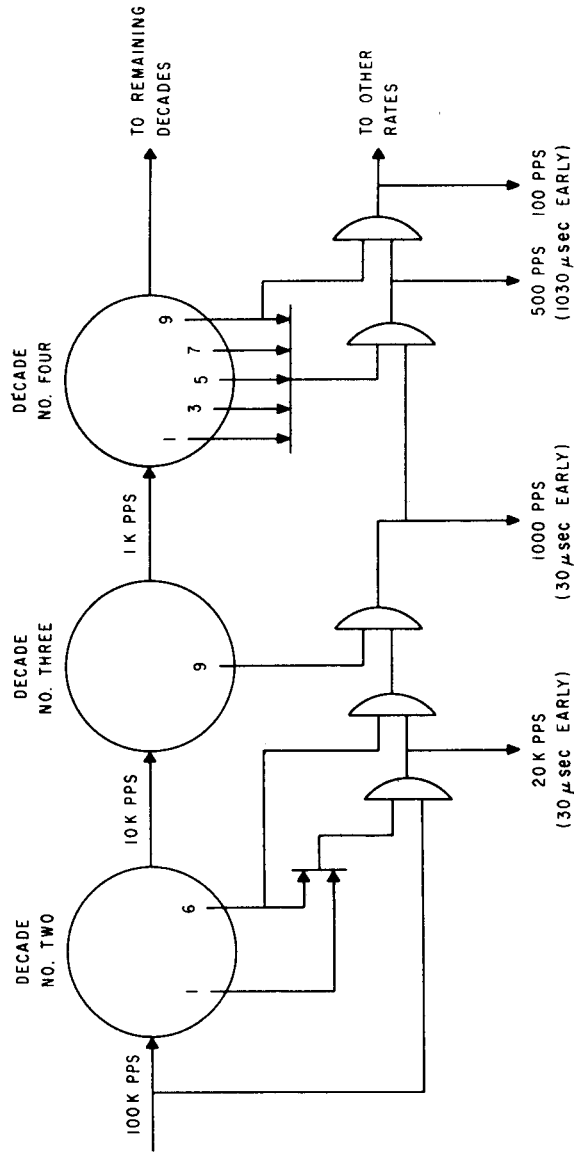


Fig. 8. Rate generator.

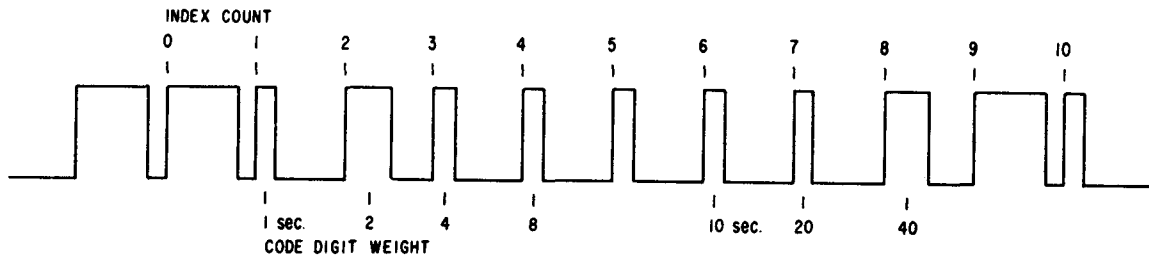


Fig. 9. Example of a 100-pps time code.

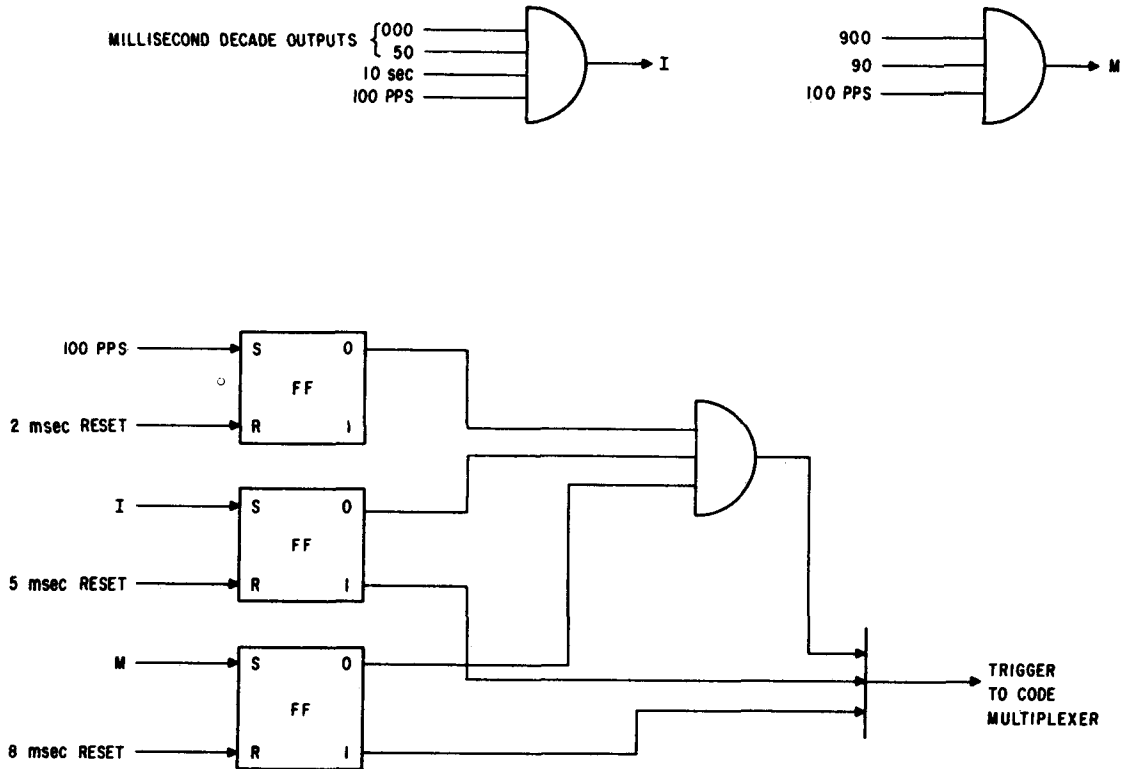


Fig. 10. Example of a 100-pps time code generator.

**Errata to Widely Separated Clocks With Microsecond Synchronization and Independent Distribution Systems.**

p. 14, Figure 10 -  
Output from FF No. 1 should come from "1" instead of "0".

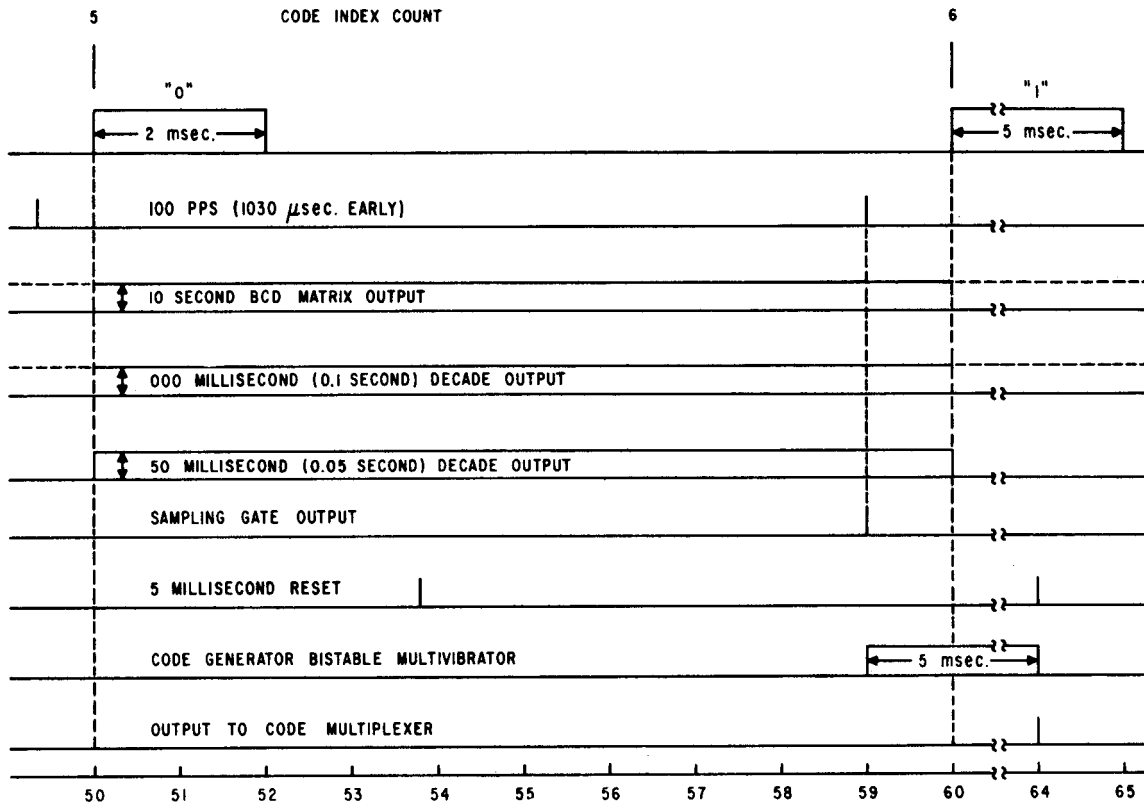


Fig. 11. Code generator timing diagram.

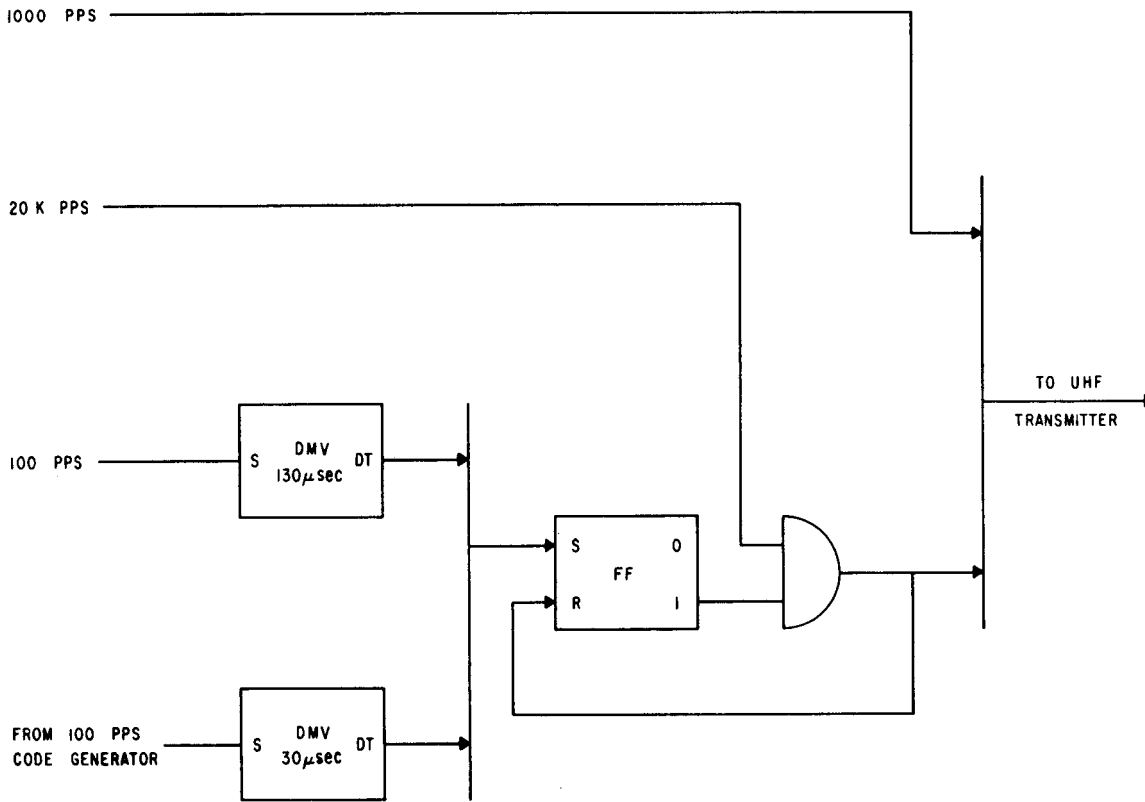


Fig. 12. Code multiplexer.

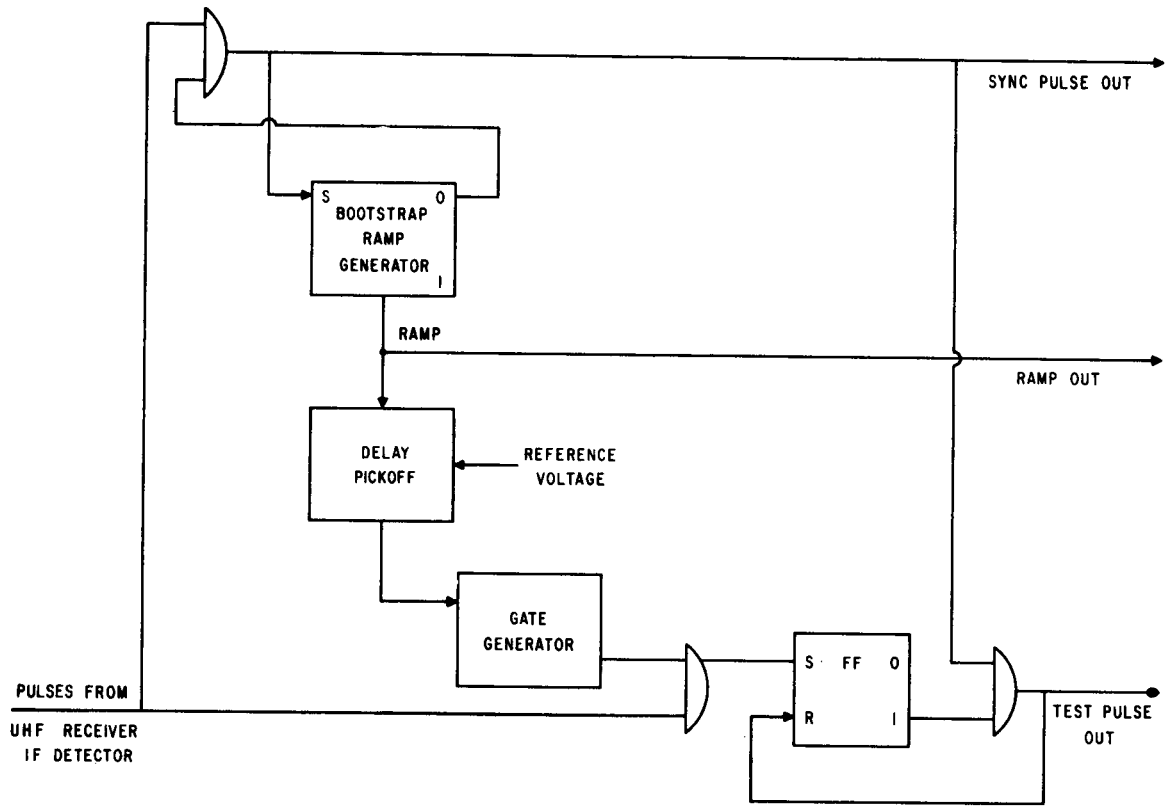


Fig. 13. Synchronization interval demodulator.

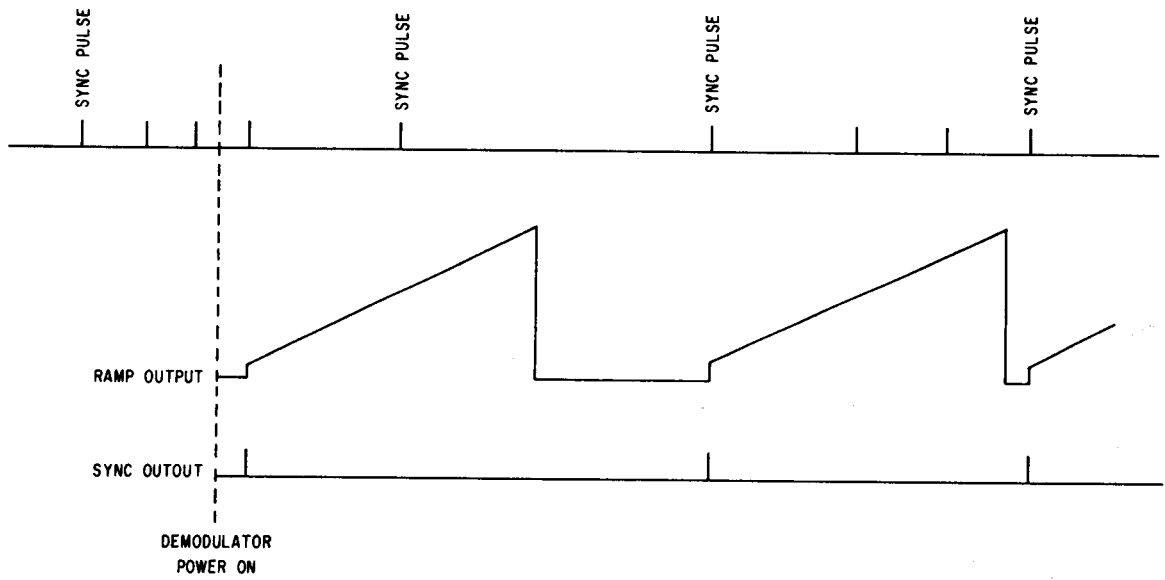


Fig. 14. Demodulator synchronization.

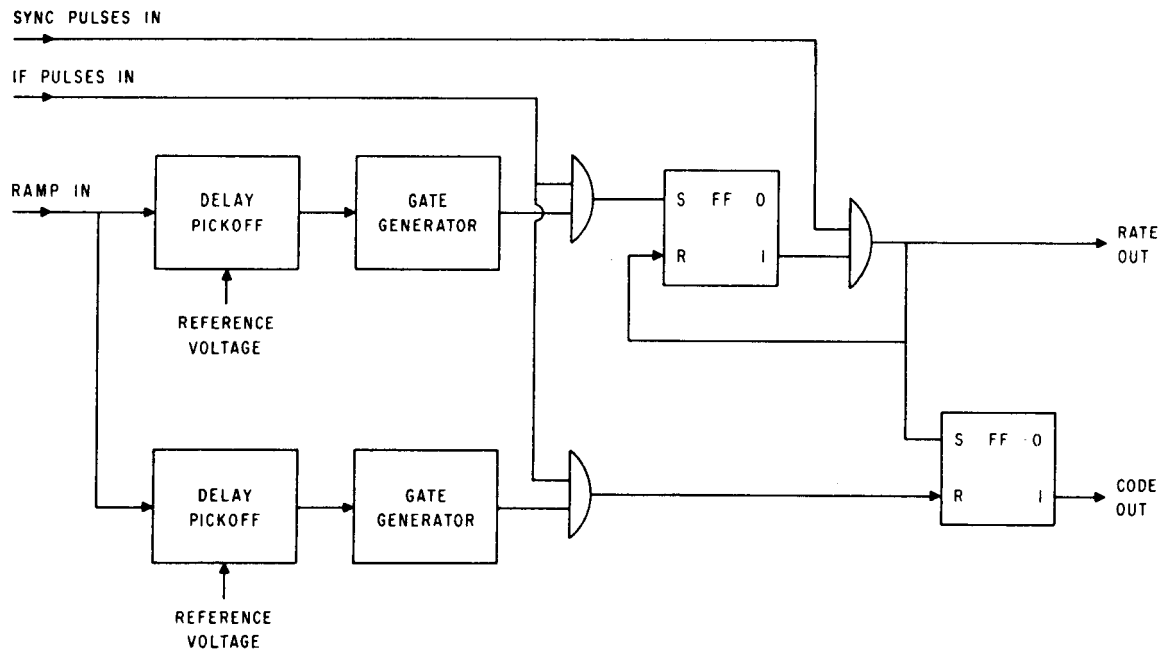


Fig. 15. Time code demodulator.

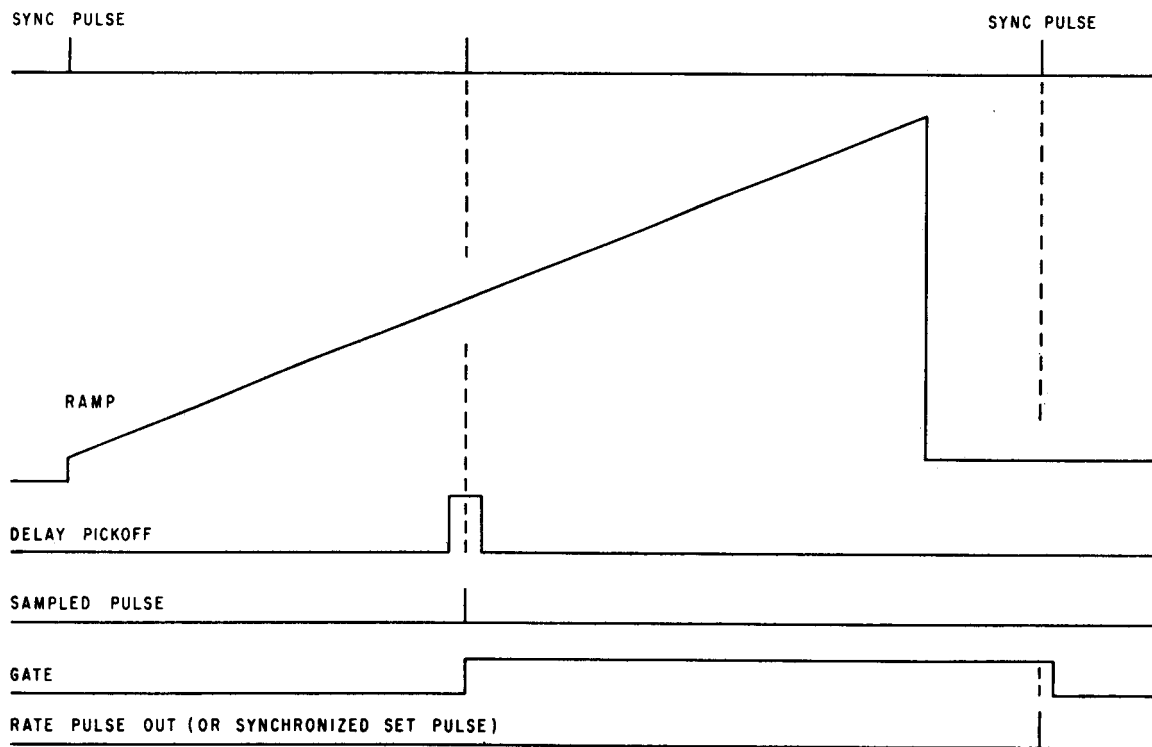


Fig. 16. Demodulator timing diagram