VLF

by Robert Stone*

Since 1960 the Navy has employed its high-powered VLF system as a means of rating precision frequency oscillators at remote points. The wavelengths of these frequencies (15 KHz to 35 KHz) are sufficiently long, compared to variations in the length of the propagation path, that phase tracking of the received carrier at remote points, even after several reflections, can be easily accomplished. Atomic standards at the transmitter provide frequency control of better than one part in 10^{11} and permit the rating of oscillators at the received point to better than one part in 10^{10}. Prior to this system, HF radio time signals were employed which had an accuracy of about 1 msec. This system was capable of rating oscillators to about one part in 10^{8} on a day-to-day basis. At the present time, there are seven of these high-powered VLF transmitters as shown in Figure 1. (A recent installation has been made, NDT, in Yosami, Japan.) New antenna systems are being installed in Hawaii and Annapolis. Some of these stations have been operating since the mid-1930's, at which time they employed tuned circuits at the input and intermediate stages. At the present time, all stations have been updated with broadband amplifiers and they employ tuning only at the output/antenna. The newer system greatly simplifies the transmission of time signals.

Operation in the CW mode is quite simple, since all that is required is a precision reference for the carrier. Frequency shift keying (FSK) presents a somewhat more difficult problem. The format used for the VLF

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SCHEDULE OF TIME AND FREQUENCY TRANSMISSIONS ON VLF FROM U.S. NAVAL RADIO STATIONS

Station	Location	Frequency (kHz)	Nominal Radiated Power (kw)	Maintenance	Special Transmissions
NAA	Cutler, Maine 44°38!9N, 67°16!9W	17.80	1,000	1400 to 1800 UT each Friday	FSK for two hours followed by CW for one hour. Phase stable on 17.80 but not on 17.85 kHz.
NBA	Balboa, Canal Zone	24.00	150	1200 to 1800 UT each Monday	Time signals on CW Morse from 55 to 60th minute every even hour except 2355 to 2400 UT. FSK continuous at other times. Phase stable on 24.00 but no on 24.05 kHz.
NLK	Jim Creek, Washington 48°12!1N, 121°55!0W	18.60	250	1000 to 1500 UT second Thursday of each month	FSK continuous except five minutes before each even hour on locked key. Phase stable on 18.60 but not on 18.65 kHz.
NPM	Lualualei, Hawaii	23.40	140	1700 UT Monday to 0200 UT Tuesday 1st and 3rd Monday of each month.	FSK continuous. Phase stable on 23.40 but not on 23.45 kHz.*
NSS	Annapolis, Md.	21.40	85	1300 to 1900 UT each Wednesday	Time signals from 55 to 60th minute each hour. CW Morse continuous. Phase stable.
NWC	North West Cape, Australia 21°49!0S, 114°09!8E	22.30	1,000	0000 to 0300 UT each Monday	FSK and CW. Phase stable on 22.30 but not on 22.35 kHz.

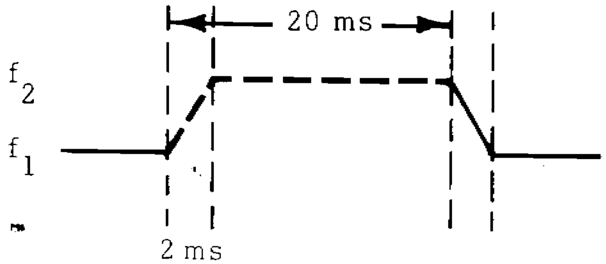
FIGURE 1

frequency shift signal is shown in Figure 2. The bandwidths of the antenna systems at these frequencies are narrow and they restrict the speed and magnitude of the carrier shifts. A 50-baud 7.0 teletype code is employed. The bit lengths are 20 msec and the transition time between the stabilized points of the carrier is 2 msec. Fifty cycle carrier shift is employed.

To permit the use of phase-coherent receivers for phase comparison at the remote sites, it is necessary that the carrier being measured be continuous in phase, as shown on the lower portion of Figure 2. Because of the high power involved and the high Q of the antenna system, phase discrepancies at the point of transition will provide transients which result in high voltage flash-overs in the transmitter. Where two carriers are employed, it is necessary that the transition between them occur at a point of phase coincidence. Fortunately, with bit lengths of 20 msec and carrier separation of 50 cycles, phase coincidence will occur at each transition point. However, at the time of the installation of the FSK system, it was not operationally feasible to precisely control the bit lengths; therefore, one of the carriers was controlled in phase to maintain phase coincidence at the transition point and the other carrier was phase-controlled relative to the reference standard. In actual operation, the frequency of the phase-controlled carrier is set at the station assigned frequency and the other carrier is offset 50 cycles either above or below the assigned frequency. At the remote receive end, the on-frequency carrier will be phase-stable except for propagation variations and the offset frequency carrier will contain the small phase variations which were required to compensate for the variation in the timing of the teletype bit stream.

The instrumentation which is now available at all VLF stations is shown in Figure 3. A cesium beam reference standard is used to drive a divider bank which produces the frequencies needed in the synthesizer and also to provide two frequencies, 50 cycles apart, to be used by the

VLF FSK SIGNAL FORMAT



50 Baud

7.0 Code

Covered

50 Cycle Shift

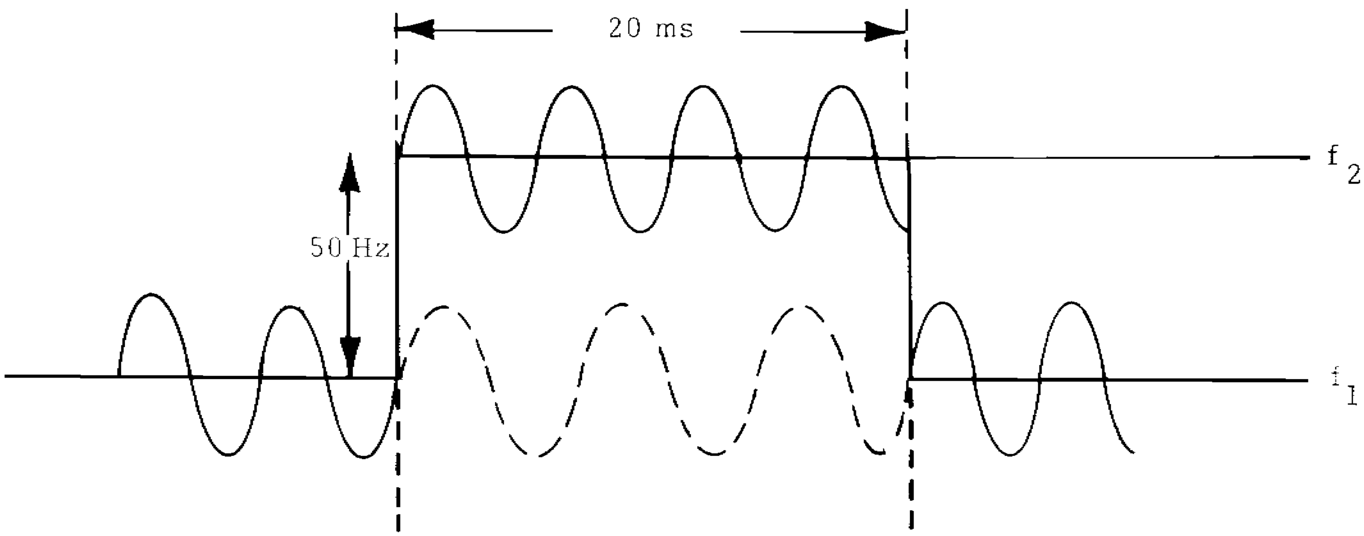


FIGURE 2

PHASE COHERENT FREQUENCY SHIFT KEYING GENERATOR

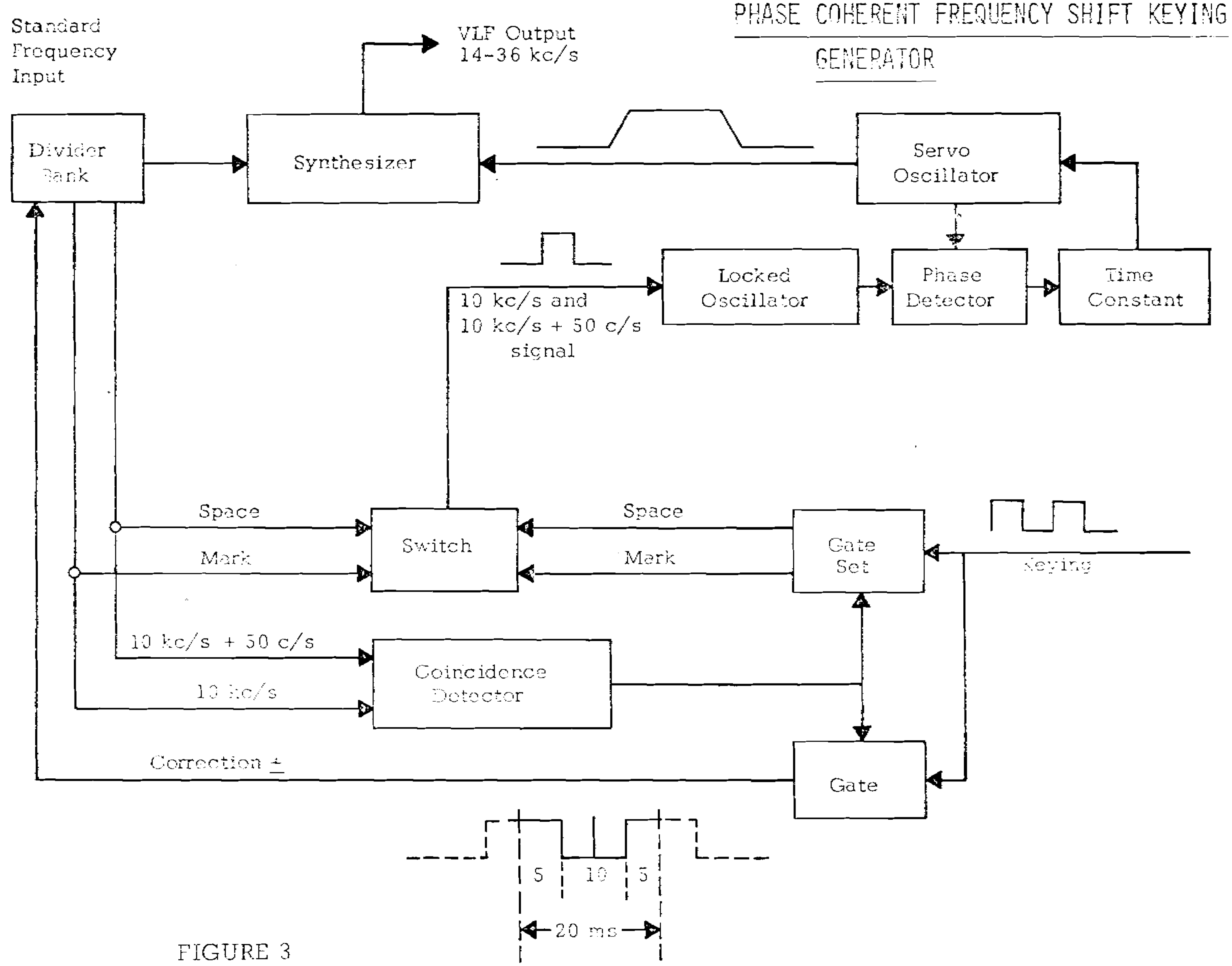


FIGURE 3

keyer. These two frequencies are fed into a switch and also into a coincidence detector. The input key stream sets a gate which is activated by the coincidence pulses. The output of the gate in turn activates the switch in response to the input keying at the phase-coincidence points between the two frequencies. The shifted output from the switch is converted to a sine wave by a locked oscillator and controlled in shift time by the time constant of a servo-controlled oscillator. This output is mixed with the frequencies in the synthesizer to produce the VLF control frequencies of 14 to 36 KHz.

Recently, emphasis has been on controlling the point of transition of the FSK signal at a precise rate and a defined time. A system has been developed and will be put into operation at the Northwest Cape, Australia installation in January 1971. When a communications system is used for precision time and frequency purposes, it is necessary that the communications aspects of the system be preserved. In the case of the VLF system, the teletype code stream carrying the information is generated in a remote classified area and is "covered." Several sources of error must be recognized and compensated for by the system. First, noise bursts sometimes occur on the control line, producing extraneous bits or "hits"; second, at certain times erroneous or non-controlled (that is out-of-time) signals may be imposed on the line; and third, some mistiming may occur between the keying stream and the precision time stream generated from the standard. A block diagram of the storage/retimer portion of the equipment is shown in Figure 4. The first portion of the circuit consisting of a gate, a flip-flop, and a count to 12 is, in effect, a digital low pass filter which must have a count of 12 msec before it will acknowledge a change to MARK or SPACE. This circuitry quite effectively eliminates narrow noise bursts. The second portion of the circuitry, consisting of the phase detector, 2 counts to 14, and a count to 16, recognizes an out-of-time or randomly keyed signal. Fourteen out of sixteen bits must indicate an error in timing for the system to recognize and make a timing correction. It is expected that timing errors of several parts in 10^7 may occur between the incoming bit stream and the clock-controlled bit stream. To compensate for this discrepancy, an eight-bit storage has been included. Also, a display has been provided which will indicate the number of bits in storage. The storage retimer unit is placed in the keying line which drives the FSK keyer.

The use of the storage retimer unit allows the transitions to be set so that the center of the transition is on epoch time relative to the clock at the station. The expected accuracy of this point is about $\pm$ 10 msec as shown on Figure 5. The zero crossing of the positive-going side of the sine wave of the on-frequency carrier is also controlled to within $\pm$ 1 msec, which is about the accuracy one can obtain by a phase recording of the carrier. Identification of the transition to within 10 msec will allow the selection of a particular cycle of the carrier and the identification of the cycle crossover will yield a precision in time of $\pm$ 1 msec. It should also be noted that the phase coincident point between the two carriers will occur at the halfway mark of the transition. This permits the use at the remote received point of a system somewhat similar to that used by the Bureau of Standards, in which an oscillator can be phase-controlled by each of the carriers, then, when mixed together in a coincidence detector, will yield 20-msec markers. No data has been taken to determine the accuracy of this system when propagation anomalies are included; however, the coincident point at the transmitter is controlled to better than $\pm$ 1 msec.

The control of the transition of the FSK will provide time markers at 10-msec intervals throughout the communication; however, for many cases, it is necessary to periodically identify seconds, minutes, and hours. The simplest method of accomplishing this is to periodically send time signals. Figure 6 is a block diagram of the FSK/time signal code keyer. It consists of a series of gates-controlled outputs from a digital

FSK/TIME SIGNAL CODE KEYER

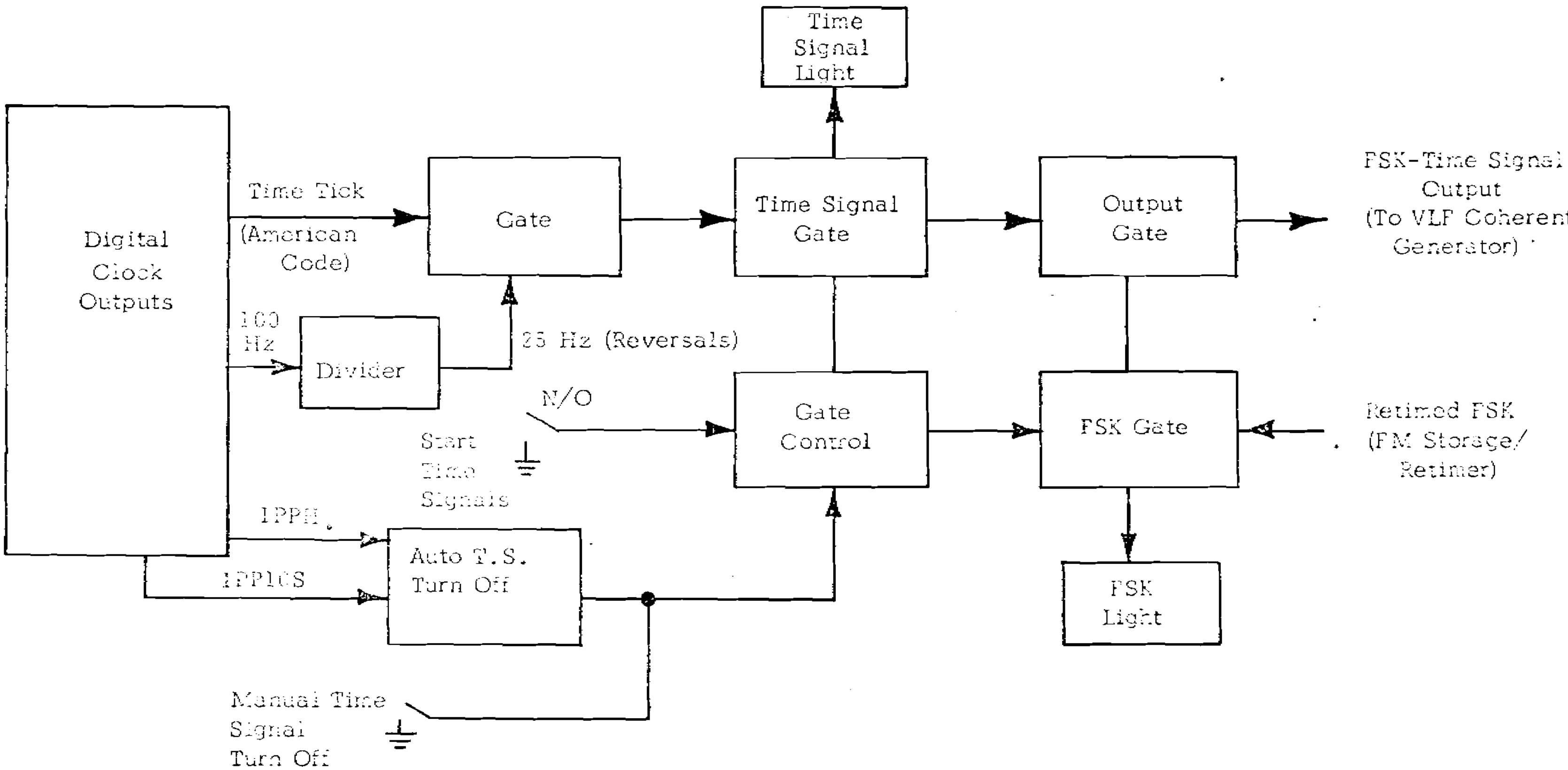
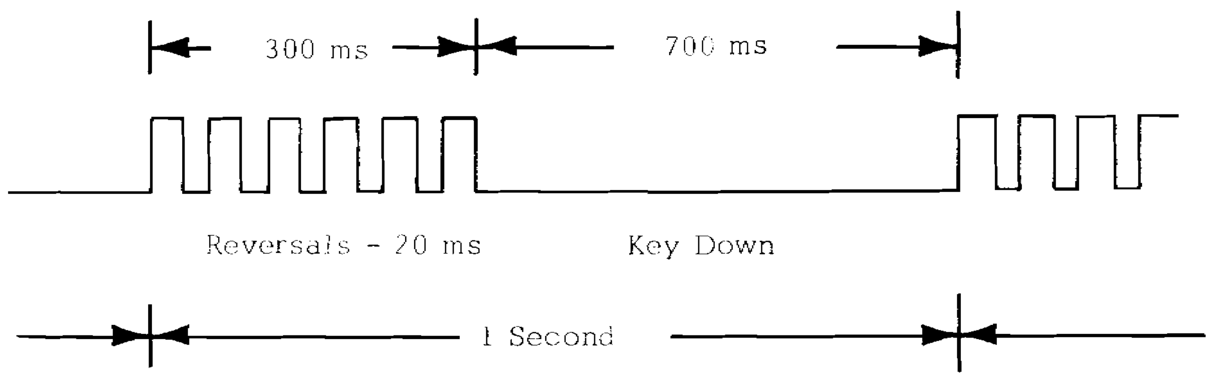


FIGURE 6

clock, such that "time" in the American code can be transmitted when desired. A diagram of the code pulse is shown in Figure 7. The first 300 msec of the code consists of 20-msec reversals, followed by a 700-msec steady signal of the offset carrier. The beginning of the second occurs at the half transition point of the start of the reversals. The time which is produced at the remote receiver is very easily recognized by ear. Present plans in cooperation with the Australian Government are to begin time signals at two minutes before 0430 and 1630 in the NWC transmission.

Figure 8 is the format of the American time code. The 29th second is omitted from every minute, then there are seconds omissions according to the table which indicate the minute for the time mark. The time mark itself is followed by a one-second tone.

TIME CODE VLF



America Time Code - Begin 2 minutes before 0430 and 1630.

FIGURE 7

TIME CODE FOR U.S. NAVAL RADIO STATIONS (AMERICAN CODE)

Time signals (dashes) are transmitted for each second of the five minute period with the following exceptions:

a. Omit 29th sec/min.

b. Second omissions permit minute identification.

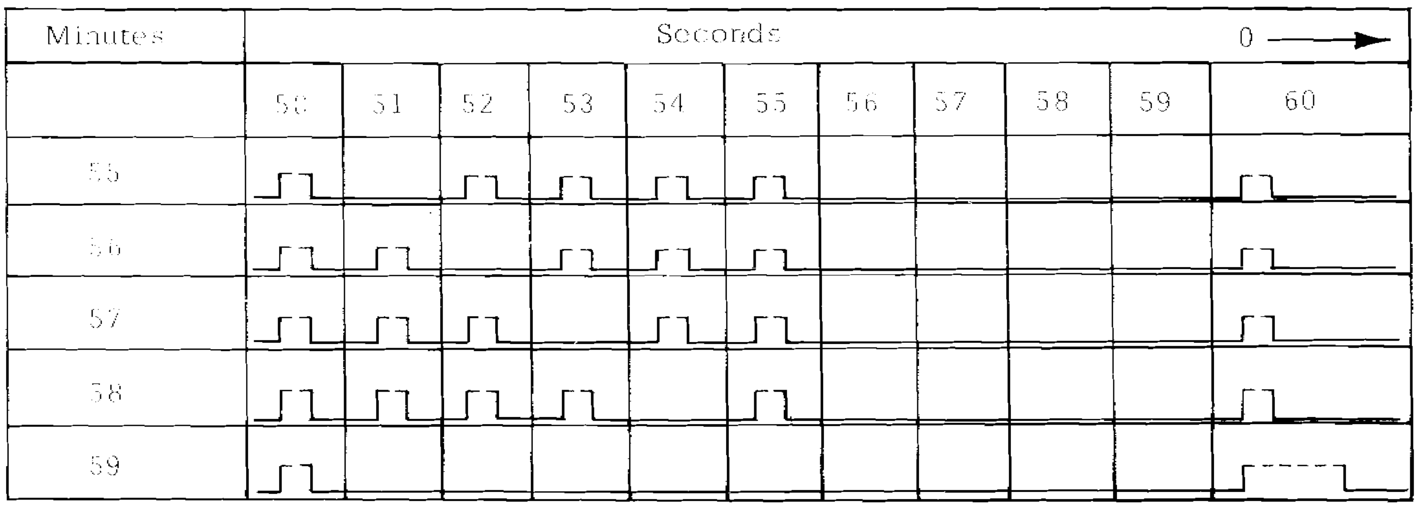


FIGURE 8