CRPL PREPRINT 50-6 ISSUED AUGUST 26, 1949

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
CENTRAL RADIO PROPAGATION LABORATORY
WASHINGTON, D. C.

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ABSTRACT

An experimental standard-frequency broadcast station, WWVH, was set up at Maui, T. H., so that data might be collected and used in determining answers to many problems which have arisen in connection with extension of standard-frequency time-signal service by operation of more than one station on the frequencies internationally assigned for such services. This paper describes the site chosen for WWVH and the experimental equipment used in establishing and maintaining it. Good results have been obtained at a temporary location.

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I. INTRODUCTION

Results of the International Telecommunications Conference, held at Atlantic City in the summer of 1947, included agreements that all standard-frequency broadcasts be confined to narrow channels centered on 2.5, 5, 10, 15, 20, and 25 megacycles. For a number of years all of these frequencies have been used by the National Bureau of Standards radio station WWV to transmit standard frequencies and time signals on a continuous 24-hour basis.

In November 1948, the Central Radio Propagation Laboratory began operation of a remotely located experimental standard-frequency transmitting station WWVH, to obtain data for studying methods of effectively providing continuous world coverage of standard-frequency and time-signal services. Data on reception from this station are being collected for use in determining:

(a) Order of accuracy attainable in synchronizing two or more standard-frequency stations.

(b) Increase in the effective service area provided.

(c) Method of operating separate stations on the same frequency; i.e., simultaneous broadcasts or time division among different stations.

(d) Best locations for the different stations.

(e) Interference to present users of WWV services.

This paper describes the site chosen and the equipment and methods used in establishing the experimental station.

II. TRANSMITTING SITE

The CRPL field station at Kihei, Island of Maui, Territory of Hawaii, where an ionosphere sounding station already was in operation, was selected as being a suitable distance from Washington and having sufficient building space and land area to accommodate the experimental equipment. A photograph of the station is shown in Fig. 1. The coordinates of the site are north 20° 46'02" and west 156° 27'42". The site, about 4 acres in extent, has a maximum elevation of about 10 feet. Portions of the area are occasionally flooded during heavy rains or when the monthly high tides are accompanied by high winds. The prevailing trade winds, deflected somewhat by a nearby mountain range, are from the northeast and have a daily average maximum velocity of 25 to 30 miles per hour. The mean average daily temperature is 74°F.

The frequencies assigned to WWVH are 5, 10, and 15 Mc. Of the group of frequencies mentioned above, these three are satisfactory for investigating day- and night-time transmission conditions on a long-time basis.

III. ANTENNAS

The antenna installation presented the greatest problem and is a compromise between expediency in getting the station into operation or waiting until poles of the desired height could be obtained from the mainland. The station is located on a small point of land extending into Maalaea Bay on the south shore of Maui. The main building is less than 50 feet from the water at high tide and the area available for the antenna installation is a low sand flat, on two sides of the building, that is occasionally inundated because of heavy rains in the winter season, or when high winds prevail at semimonthly periods.

The 5- and 10-Mc antennas with additional poles for reflectors if required are shown in Fig. 2. All the antennas are vertical radiators with provision for reflectors that can be erected in approximately 5 minutes if directional transmission is desired. Both the quarter-wave 5-Mc antenna and the half-wave 10-Mc dipole antenna are supported on guyed 50-foot hexagonal sectional plywood masts. These masts were erected on concrete pedestals extending above the ground to give a firm base and also to obtain sufficient added height to insure that the antenna base insulators would be above the water level when the area was flooded.

The half-wave 15-Mc dipole antenna is supported on a 45-foot impregnated wood pole which has a braced cross-arm arrangement at the top that permits both the antenna and reflector to be supported by the same pole.

All antennas are fed by 600-ohm open-wire transmission lines constructed of No. 8 AWG hard-drawn copper wire spaced 9 inches. The open-wire type of transmission line was used because it has low loss, is easy to adjust with few instruments, is readily inspected and repaired, and is relatively reliable over long periods of time. On the 10- and 15-megacycle transmission lines, stub matching was used to minimize the standing waves. A small wooden enclosure at the base of the 5-megacycle antenna housed an rf transformer to end-feed the quarter-wave antenna. The following VSWR's were measured on the transmission lines at the completion of adjustments: 5 Mc, 1.18; 10 Mc, 1.02; and 15 Mc, 1.08. Tests were also made to determine the effect on the SWR when the reflectors were used. In no case did the standing-wave ratio exceed 1.5. This change was not considered sufficient to justify readjusting the line-matching transformers if directional transmissions were desired for certain tests.

IV. TRANSMITTERS

The transmitters used in this installation, shown in Fig. 3, were commercial units applicable for operation in remote locations. They were designed to minimize the number of types of vacuum tubes and circuit components that must be stocked in order to insure consistent operation. The rectifier is a stationary unit accessible from the front and rear for service operations. The associated radio-frequency and modulator units are the roll-out type accessible from one side for routine maintenance operations.

The rectifier unit with its associated plate transformer is capable of supplying bias, low and high plate voltages for as many as four units, i.e., four CW channels or two modulated channels. As used at WWVH one rectifier normally supplies power to a single modulated channel but may supply a second channel in emergency.

The high and low voltage rectifiers use type 872-A tubes in conventional circuits, and most of the component parts are interchangeable. The radio-frequency unit has an output of 3 kilowatts at any one frequency in the band of 2 to 20 megacycles. A type 807 tube is used in a frequency doubling stage, a 5D24/4-250A as an intermediate amplifier and a forced air-cooled WL473/5736 in the final output stage. Power and space were provided for an internal crystal if desired. This space was used for circuits to multiply a 2.5-megacycle standard frequency to 5 and 7.5 megacycles for excitation of the transmitters used on 10 and 15 megacycles. The transmitters, when modulated 100 percent with sine-wave audio power, are capable of delivering 3 kilowatts continuously of carrier plus sidebands into a balanced load of 600 ohms. When properly adjusted the total harmonic content in the output is 45 to 50 db below the fundamental.

The modulator unit has push-pull amplification throughout and is provided with peak limiter and automatic gain control circuits that are easily switched in or out of the circuit as required. Audio input at 600 ohms impedance is transformer-coupled to a pair of 6SK7 tubes which in turn are transformer-coupled to a pair of 807 tubes in the intermediate amplifier. The stage is capacitively-coupled to another pair of 807 tubes as cathode-follower driver tubes for the final 833-A modulator tubes. The modulator unit is capable of delivering 1.8 kw of sustained sine-wave power.

V. STATION EQUIPMENT

In equipping a standard-frequency transmitting station important considerations are accuracy, reliability, and freedom from spurious emissions. A detailed discussion of the accuracy of frequency and time signals is not within the scope of this paper. In planning a transmitting station, the efficiency and operating costs of the transmitters must be considered. Radio transmitters are not yet available which operate unattended at high efficiency for long periods of time without maintenance. Sealed units having such characteristics would be most desirable and may eventually be obtainable. Power for the station should be reliable and constant in voltage. Continuous power requires duplicate or triplicate sources either from local generators or from separate utilities connected by different routes to the transmitting station or a combination of these methods. The equipment should be protected by suitable finishes, air filtering and drying if deterioration by fungus, blowing sand or salt spray is probable.

The most important part of a standard-frequency station is a frequency-time standard of great accuracy and stability to control the transmissions. Quartz-crystal controlled oscillators are the best yet available for this purpose. These oscillators should be provided in triplicate to insure accuracy of the broadcasts and to enable local comparison between the different oscillators to determine more easily which particular oscillator varied in drift rate and by how much. To insure the continuity of the broadcasts, provision should be made for duplicate installations of radio- and audio-frequency control equipment. These separate sets are periodically adjusted to maintain very close agreement with each other. Upon failure of any unit in the chain from piezo oscillator to control output, the alternate set is used to control the broadcasts.

Certain portions of the submultiple equipment as well as the piezo oscillators must be kept operating during periods of power failure. For this purpose a set of plate and filament storage batteries and the necessary float chargers are provided for each control channel.

In order to facilitate the installation of WWVH, a complete set of frequency and time control equipment from WWV was revised and reinstalled in Hawaii. Revision consisted of providing rack-mounted piezo oscillators and relocation of some units. The present installation is shown in Fig. 4. Another oscillator and set of frequency and time control equipment for WWVH are being provided.

Referring to Fig. 4, rack No. 1 on the left contains a 100-kc frequency standard with its associated amplifier to furnish two isolated 100-kc outputs. One of these outputs is used to furnish excitation for the radio-frequency multiplier equipment and the other to control the audio-frequency derivation equipment for the production of time signals and modulation frequencies.

Rack No. 2 (left center) includes the following equipment starting at the top:

(a) Telegraphic code time announcer for giving the correct time every five minutes in GMT, by means of telegraphic code, starting on the 35th second of every announcement interval.

(b) Keying device for identification of the station. This unit keys the call letters WWVH twice in telegraphic code 5 seconds after the completion of the time announcement.

(c) Frequency multiplier consisting of a single-stage 100-kc amplifier and two push-pull quintupler stages.

(d) Radio frequency distribution amplifier using four type-807 tubes with the grids driven in parallel but with individual isolated plate output circuits delivering two watts at 2500 kc to 70-ohm coaxial lines for transmitter excitation.

(e) 100-Kc piezo oscillator, its associated amplifier, a power supply voltage filter and voltage regulator unit.

As 2.5 Mc is the lowest standard frequency that may be transmitted, it is economical to multiply the control frequency to this value in one unit, thus materially reducing the number of multiplier stages required in the individual transmitters. The 100-2500 kc multiplier output is approximately one watt into a 70-ohm line. Unwanted harmonics are down 50 db and modulation products are attenuated by more than 70 db. Type-807 tubes operated very conservatively were used in the balanced quintupler stages to insure reliability.

Rack No. 3 contains the following equipment, starting at the top:

(a) A second telegraphic code time announcer unit, which operates in conjunction with the one on top of the adjacent rack, and acts as a check unit to remove all time signals from the air if either of the two units falls out of step with the other.

(b) The next unit contains three single tube circuits: two 10-to-1 frequency dividers furnishing a 1-kc output from a 100-kc input and an amplifier for 1 kc.

(c) The third unit on this rack is a phase shifter and frequency divider.

(d) The next panel in the chain contains a divider, modulator, and multiplier unit.

(e) The following unit is a monitoring panel for aurally checking the audio signals used to modulate the transmitters.

(f) The next two units generate the pulses and control the make and break of the tone modulation to give the long interval signals.

(g) Immediately below the mixer amplifier unit are the four gain controls for adjusting the modulation level of the transmitters.

(h) The bottom unit on this rack is a regulated power supply for the mixer amplifier unit.

All but the top unit on this rack are used in derivation of the standard audio frequencies, standard time and time interval signals occurring at intervals of 1, 4, 5, 9, 10, etc. minutes. A block diagram showing the functions of this equipment is given in Fig. 5.

The dividers employ tubes operating as class A amplifiers with voltages from tuned circuits in the plate reflexed and mixed with the input frequency in a balanced modulator circuit. The modulator type of divider has a distinct advantage in that it does not self-oscillate but requires an externally supplied input voltage of the proper frequency before any output voltage can be obtained.

The large dial at the left of the third unit is on the rotor shaft of a selsyn unit operating at 1000 cycles. By manually turning the rotor, cycles can be added to or subtracted from the input frequency. This phase shifter permits the time signals generated in a later unit to be advanced or retarded and set in exact agreement with any time signal. With the unit it is possible to set the seconds pulses from two similar divider chains in agreement within ± 2 microseconds using an ordinary oscilloscope. The frequency divider operating from the output of the phase shifter furnishes output voltages at 500, 300, and 100 cycles.

The frequency divider in the fourth unit, excited by 300 c, has an output at 60 c. In a balanced modulator supplied with 60 and 500 c the output is 440 and 560 c. This output is passed through a filter network which rejects the 560 c and passes 440 c, the standard of musical pitch corresponding to A above middle C.

The 1000 c is used to excite a frequency multiplier which has an output frequency of 4000 c. A mixer unit is provided for furnishing a tone consisting of equal amplitudes of 440 and 4000 c for modulating the transmitters.

The 100- and 1000-c from previous units are mixed in a balanced modulator circuit and a series of pulses, each consisting of 5 cycles of 1000 c, is generated. In order to produce good sine-wave pulses, a phase shifter is provided in the 100-c circuit to adjust the phase so that both voltages are at zero simultaneously.

The 60 c from the previous unit is converted into 2-phase 60 c which is amplified to drive a self-starting synchronous motor having an output shaft speed of 1 rps. A set of contacts operated by a cam on the 1-rps shaft is closed each revolution for a period of about 10 milliseconds. This mechanical gate allows one pulse per second from the 100 pulses per second to pass into an external circuit.

By reduction gears the clock motor also drives cam shafts which have speeds of 1 rpm and 12 rph. Exactly on the proper minute of the five-minute interval in the hour and on the proper second of the minute these cams close switches and channel a seconds pulse into one branch of an electronic switch. This switch operates, and in so doing puts cut-off bias on the tone branch of the mixer amplifier unit and establishes normal operating bias on the announcement branch. Whatever intelligence is desired is passed through the announcement branch to modulate the transmitters.

Exactly one minute later on the hour and each five-minute interval thereafter another seconds pulse is channeled into the electronic switch where it operates to put cut-off bias on the announcement branch of the mixer and to establish normal operating bias on the tone branch.

From the foregoing it can be seen that the mechanical contacts function only as gates to channel the seconds pulses into the proper circuits. The seconds pulse derived from the 100-kc standard is the determining element in the accuracy of the time intervals.

VI. MONITORING EQUIPMENT

Rack No. 4 at the right, Fig. 4, contains the remote control equipment and monitoring recorder, as well as the equipment for monitoring WWV, in order to maintain the accuracy of the frequency and time signals of WWVH.

(a) The top panel on this rack contains the relays for synchronizing the operation of the WWVH and the ionosphere sounding transmitters.

(b) On the second panel is a manually operated remote control unit for the WWVH transmitters. The push-button type switches shut off the transmitters completely. The rotary-type switches permit the removal of the plate voltages of the rf modulator or rectifier units as desired.

(c) The time recorder for monitoring the automatic features of the installation is mounted on the third panel.

(d) Other equipment on this rack is used for maintaining the WWVH oscillators in agreement with the WWV transmissions.

The ionosphere sounding transmitter operates on the hour and half-hour and in one-minute sweeps through the range 2.2 to 16 megacycles. Supplementary manual observations are required when the vertical-incidence critical frequency exceeds 16 Mc. Some means had to be provided for synchronizing the two sets of equipment as the high fields from WWVH signals caused unsatisfactory records from the sensitive automatic ionosphere equipment. This was accomplished by means of two cam-operated switches on the clock unit operated from the frequency standard. One switch is closed for a very short period of time to send a starting pulse to the sounding transmitter. The transmitter automatically shuts off after completing the sweep. Coincident with the above, a long-period cam operates a switch to shut down the WWVH transmitters. These transmitters remain off for 4 minutes and 20 seconds to permit manual ionosphere observations if required. The interval of 4 minutes and 20 seconds is the maximum amount of time that will permit WWVH transmitters to mark accurately the hour and 30-minute intervals before shutting down and still permit them to return to the air in time to give the telegraphic code announcement for the 5- and 35-minute intervals.

The recorder in the third panel of the rack at the right is equipped with 20 relay-operated pens. Each relay coil circuit is isolated and will operate from either 110 volts ac or low-voltage dc. There are three pen circuits per transmitter, one each for the rectifier, modulator, and radio-frequency unit. Their purpose is to record the time and number of momentary overloads or a complete failure of the unit. Where equipment is operating unattended several hours every day a record of this type facilitates the location of faults causing transmitter outage, or in the case of recurring overloads in a particular unit, indicates impending failures. Additional pens are connected across modulation control circuits to indicate that the tone is removed for one minute every five minutes and also that the time announcement and station identification keying units are functioning correctly. Pens are also connected to the heater circuits in the 100-kc frequency standards to indicate proper operation and any changes in the heater cycle caused by changes in ambient temperature.

Agreement with WWV transmissions is determined either by direct frequency comparison or by obtaining an average frequency for a period derived from the time kept by the synchronously-driven local clocks compared with the time signals transmitted by WWV.

The ideal monitoring system would require a separate receiving site located to the east of the WWVH transmitting station. Highly directive receiving antennas would provide sufficient discrimination to permit simultaneous reception of both stations. Continuously operating recorders on each of the transmitted frequencies would provide a permanent record of the frequency and time differences between the two transmitted signals.

In the present installation the monitoring is done at the transmitting site which requires that the WWVH transmitter be shut down for a period twice daily, at 0700 and 1900 GMT, to permit reception of WWV. The harmonic relationship of the frequencies to be received from WWV made it possible to erect a simplified wide-band antenna which had a major lobe oriented on Washington, D. C.

Located below the time recorder is a harmonic generator unit and the associated HF radio receiver used in making direct comparisons in frequency between the local standard oscillators or one local oscillator and the WWV received frequency. The harmonic generator consists of two identical units, each provided with a gain control to adjust the injection level into the receiver. To compare the local oscillators the receiver is tuned to the desired harmonic and the input connected to the harmonic-generator output terminals. Each harmonic generator is controlled by a separate frequency standard and the levels are adjusted for equal amplitude by means of the S-meter in the radio receiver. The aural beat note may be counted by observing the swing of the S-meter pointer as the phase relationship of the two frequencies changes. A number of independent checks are made on the time required for a fixed number of beats. These values are averaged and this averaged value is used to obtain the frequency difference. In a unit length of time the accuracy of intercomparing the standard oscillators increases by a factor equal to the harmonic order at which the measurement is made.

When the frequency of one of the local standard oscillators is to be checked against WWV, the receiver obtains its input from the antenna and one of the harmonic generators. The receiver is tuned to an assigned frequency, for which transmission conditions are optimum, in order to minimize the effects of fading. The measurement procedure is the same as outlined in the above paragraph.

Frequency determinations made by checking the time kept by the local clocks are accomplished by comparing the local and received seconds pulses on a cathode-ray oscilloscope. The linear sweep is controlled at 60 c from an external source obtained from the standard-frequency generators. While alternately observing the position of the local and received seconds pulses the phase shifter is adjusted until coincidence is obtained with the earliest pulse received from WWV. Vagaries of the transmitting medium may cause two successive received pulses to vary as much as 3 or 4 milliseconds in the time of arrival. By using the earliest pulse received, adjustment is made to the pulse arriving by the shortest possible path and hence with the minimum delay in transmission.

After obtaining coincidence the phase-shifter dial is read to the nearest tenth of a millisecond. This reading, compared with similar readings taken 48 and 96 hours previously, gives the number of milliseconds that the synchronously-driven local clock has gained or lost during the period.

Since frequency is an inverse function of time interval, to determine the oscillator frequency the number of oscillations in a definite interval of time must be known. Assuming the rate of drift of the oscillator has been uniform throughout the period under consideration, the average frequency for the period is the same as the instantaneous frequency for the middle of the period. This latter method is the one normally used in maintaining the WWVH frequencies in agreement with WWV.

After obtaining agreement between the local and received pulses the phase shifter is advanced 27 milliseconds before transmissions are resumed.

This 27 milliseconds is the average transit-time for the Washington to Maui path.

VII. CONCLUSION

An experimental standard-frequency and time-signal broadcast station, WWVH, was set up at Maui, T.H. A temporary location was selected that is far from ideal because of the lack of a reliable source of power and the presence of wind-blown salt spray and sand from the adjacent beaches. As with most experimental work, results are what count and not the ideal location and operation of the equipment. Good results have been obtained to date. If the same job were to be repeated now at the same site, it is believed an approximately identical installation would be chosen.

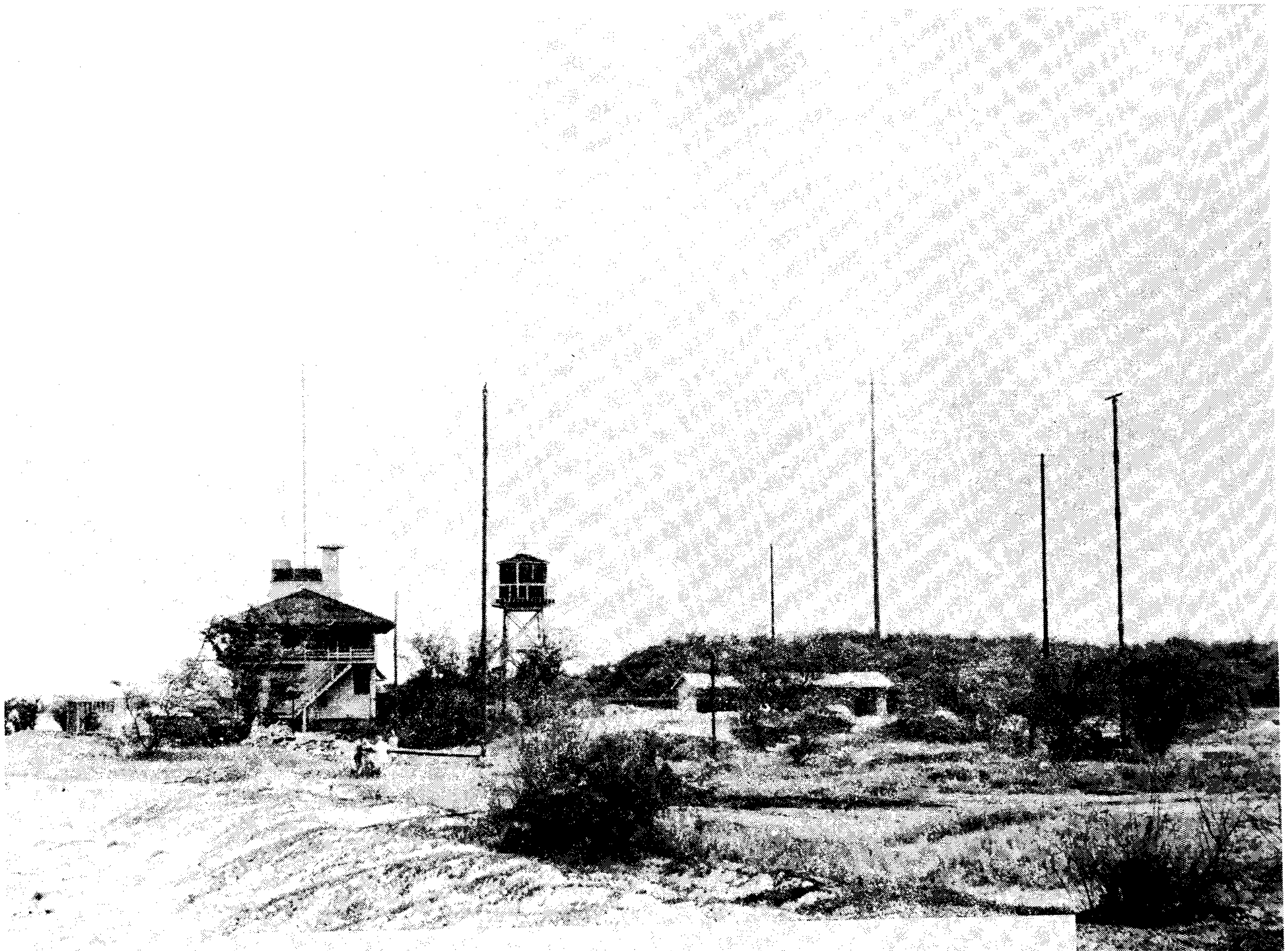

Fig. 1. View from south, CRPL Field Station, Maui, T. H. Standard frequency transmitters are located in the building to the left. Ionospheric pulse sounding equipment is in the centrally located building. Antennas for 5 and 10 Mc and wide band pusle work are shown. A 15 Mc antenna is out of the picture to the left.

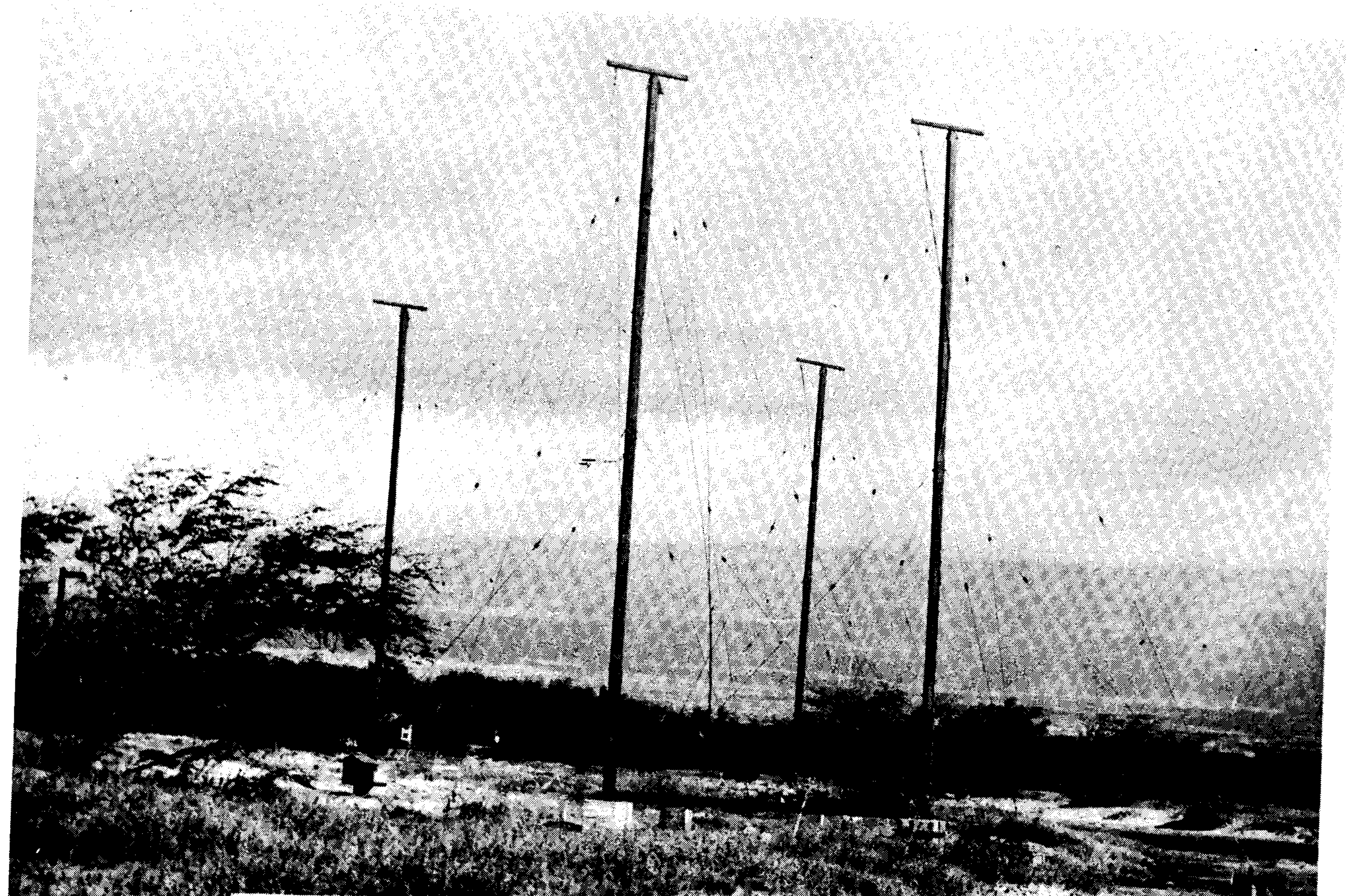

Fig. 2. Another view of antennas at radio station WWVH. In the foreground the left hand pole supports a 10 Mc, center fed half wave antenna. The right hand pole is to support a reflector if directivity is desired. In the background are similar poles for the 5 Mc transmitter. This antenna is quarter wave, end fed from the tuning house shown at the base of the pole.

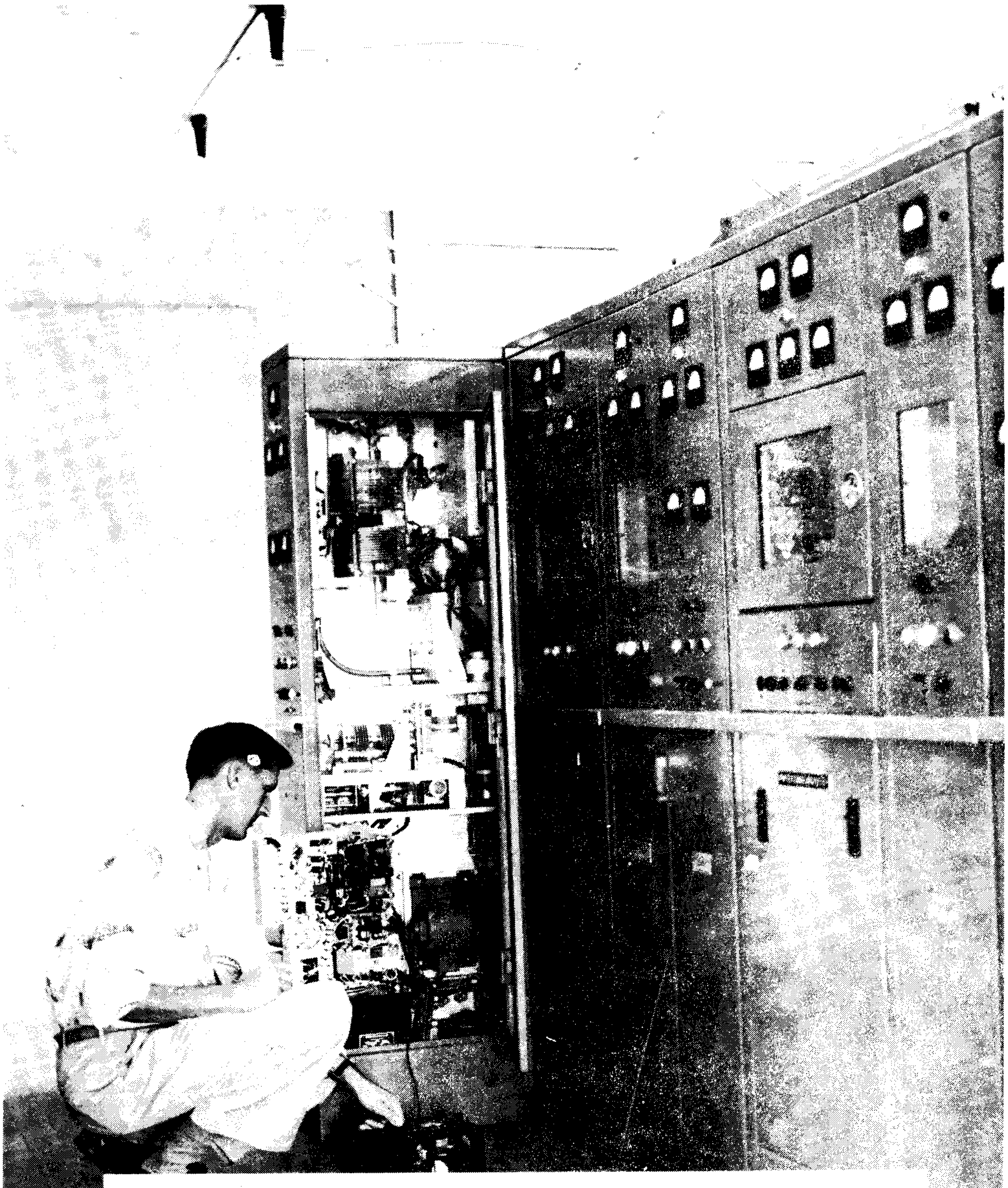

Fig. 3. WWVH transmitters. Three transmitters are mounted in line; two are shown. Units are easily rolled out for servicing. Overhead are the 600 ohm balanced r f transmission lines.

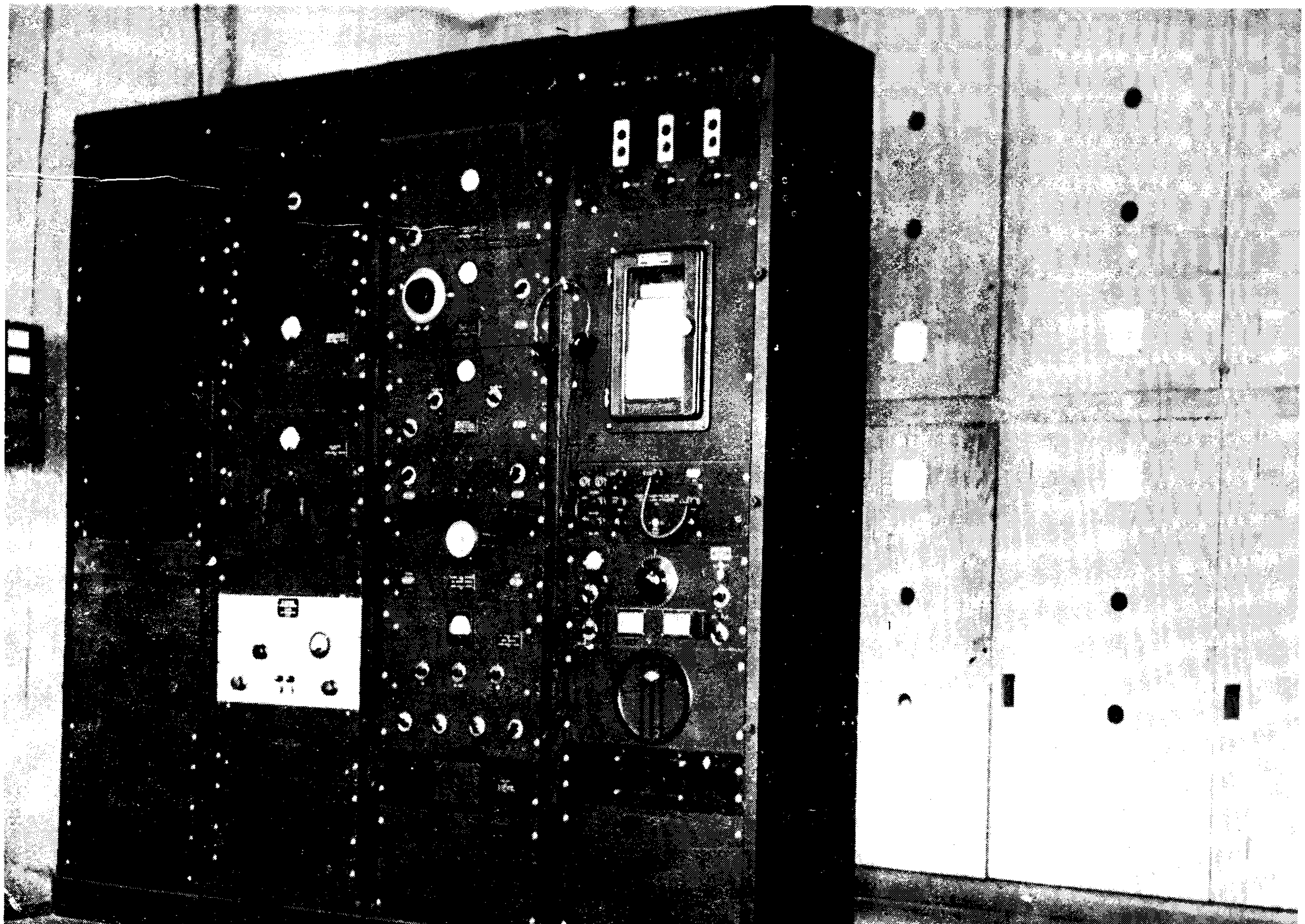

Fig. 4. Frequency-time standards and monitoring apparatus at WWVH. Left to right the 4 racks include: 1) frequency standard No. 1, 2) frequency standard No. 2 and r-f multipliers, 3) frequency dividers, clock and time interval generators, 4) control and monitoring equipment.

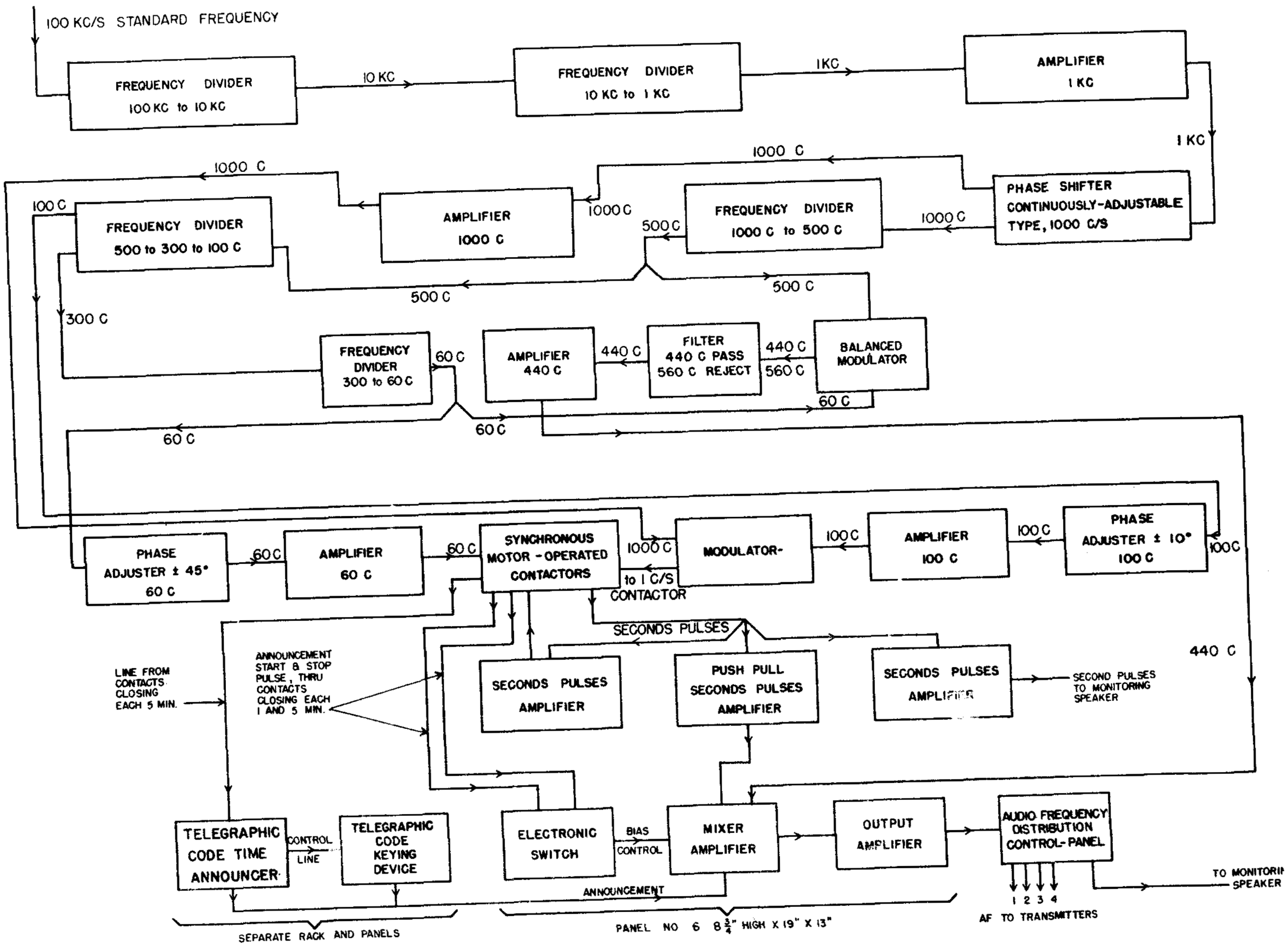

Fig. 5. Block schematic of equipment at radio station WWVH for composition of standard audio frequencies and time intervals and automatic control of time and telegraphic code announcements.