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THE MICROWAVE FREQUENCY STANDARD

A Survey of Current Microwave Frequency Calibration Techniques at the National Bureau of Standards

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NBS

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ABSTRACT[1,2]

The equipment for generating, mixing, and detecting standard frequency signals at the National Bureau of Standards in the 300 to 75,000 Mc range is described. The NBS laboratory techniques for performing precision microwave frequency calibrations are discussed.

1. INTRODUCTION

To meet the increasing needs by industry for standardization at microwave frequencies, the National Bureau of Standards created a special group to provide a microwave frequency standard and a calibration service.[3,4,5] This group is now equipped to operate between 300 and 40,000 Mc with completely standardized equipment, and above 40,000 to 75,000 Mc with equipment currently under development. It is the purpose of this group to calibrate secondary frequency standards. The secondary standard is either another microwave frequency source or a passive resonant system. The passive resonant system is by far the more compact and simpler of the two, and can have adequate precision for most applications. For example, resonant cavities are suitable standards for the alignment of radar systems, navigation, communication, and TV relay equipment, and for setting the frequency for laboratory tests on microwave components.[5] A fee schedule has been established for the Bureau service; $20 to $42 for the first frequency calibration point and $3.50 to $8.00 for each additional frequency calibration point depending on the type of secondary standard.

The standard microwave frequencies used for calibration are derived directly from one of the stable 100 Kc oscillators maintained by the National Bureau of Standards for legal time and frequency standards. The relative frequency of the driving oscillator can be determined to better than 1 part in 1 billion by reference to the other standard oscillators, and ultimately determined to the mean solar day by astronomical observations made at the Naval Observatory.[7] These are the same oscillators used in measuring and correcting the time and frequency transmissions of radio station WWV. In the course of frequency multiplication of the high order required to go from 100 Kc to the thousands of megacycles at the microwave region, some accuracy is sacrificed as a result of noise and other very tiny factors which create a phase modulation of the frequency multiplier chain. In the equipment that is now available, the frequency and phase modulation is less than 1 part in 100 million at 300 Mc, less than 1 part in 10 million at 24,000 Mc and less than 1 part in 100,000 at 54,000 Mc. The lack of accuracy at the highest frequency is primarily a result of low signal strength at the present time. In contrast, the resonant cavities and other secondary frequency standards rarely can be depended upon to better than 1 part in 10,000. A few cavities have been built which were capable of being reset to resonance to within 1 part in 100,000, but only under very carefully controlled temperature, humidity and pressure.

2. METHODS OF GENERATING MICROWAVE STANDARD FREQUENCY SIGNALS

Standard frequency microwave signals are generated by electronic frequency multiplication of the legal standard frequency source. The source driving the microwave frequency standard employs a Meacham bridge oscillator circuit[8] and a carefully, hand-tailored 100 Kc crystal[9] to get short time (10 minutes) stabilities of 1 part in 10^{10} and long time (1 week) stabilities of 1 part in 10^9. The source is frequency multiplied in a multiplier chain using simple integral factors never larger than 5. Unwanted sidebands or harmonics are suppressed 60 db at each stage of the chain. The multiplication can go as high as a few thousand megacycles in conventional grid controlled vacuum tubes, or to 25,000 Mc by using fixed-frequency klystron multipliers. Crystal rectifiers can be used for multiplication or harmonic generation and are not as frequency sensitive as the above-mentioned tubes. Crystal rectifiers used as harmonic generators in holders designed for specific frequencies are shown in Figure 1. The frequency range covered by these mounts is 300 to 75,000 Mc. Commercially available detector mounts may be used as harmonic generator mounts if the by-pass condenser in the coaxial input connector is removed permitting high frequencies to reach the crystal diode through coaxial cables. The proper harmonic from the crystal harmonic generator can be selected by a transmission cavity filter commercially available in direct reading units spread over the range from 500 to 40,000 Mc.

The Bureau uses two distinctly separate multiplier chains in the microwave frequency standard; one a fixed-frequency standard and the other an adjustable-frequency standard. The fixed-frequency standard has higher powered outputs at higher frequencies, but is not as versatile. Another major difference between these two systems is the level at which signal mixing is done. In the adjustable-frequency standard, mixing is done near the start of the multiplier chain. In the other standard, the mixing is done at the end of the multiplier chain. The advantage of low frequency mixing is the wide separation between adjacent harmonics. The major disadvantage is in the neighborhood of a few selected frequencies, where very low difference intermodulation frequencies can exist which follow up the multiplier chain and create unwanted sidebands.

For calibration activities isolated from direct connection to the standard oscillators, radio station WWV can be used as reference in synchronizing an auxiliary 100 Kc oscillator to one of the standard broadcast signals,[10] and maintains precisions of about 1 part in 10^7 if limited to sky wave propagation or 1 part in 10^8 if ground wave reception is available. The National Bureau of Standards' ammonia clock has been shown to be a reference suitable for absolute calibration to 1 part in 10^7, and to relative frequency constancy to 2 parts in 10^8.

When relatively high, standard-frequency power (for this purpose, one milliwatt is high power) is required, a frequency transfer process can be used with the usual loss of overall precision. CW klystron oscillators can be synchronized to a standard frequency. Frequency modulation of the oscillators can be minimized by using battery power and stabilizing the klystron temperature in a temperature-controlled oil bath.

3. MICROWAVE ADJUSTABLE-FREQUENCY STANDARD

Parts of the microwave adjustable-frequency standard are hold-overs of the original standard built in 1945. The block diagram in Figure 2 shows how standard signals are generated by combining a fixed multiple of the 100 Kc source with the signal from a precision adjustable oscillator. The combination frequency is adjustable by 10 per cent and passes through tunable multipliers with the same adjustment range. The 10 per cent adjustment range is expanded to 100 per cent by using the tenth harmonic of any output from the multiplier chain. Since approximately 30 Mc is the lowest output, the complete coverage begins at the tenth harmonic of 30 Mc; 300 Mc. The rf power available for harmonic generators is at least 2 watts at each output of the multiplier chain. The excellent efficiency of the harmonic generators and detector systems permits the use of harmonics as high as the 30th for calibration purposes, and extends the range of the standard through 25,000 Mc. The microwave adjustable frequency standard occupies the center two racks of the 4-rack system shown at the left in Figure 3.

The overall accuracy of the adjustable-frequency standard is reduced by only a part of the variation in the precision adjustable oscillator. The portion is determined by the ratio of the frequencies contributed from the standard and the precision oscillator at the point of mixing. The frequency of the precision oscillator can be determined by a frequency counter, or by heterodyning against known low-range standard frequencies.

4. MICROWAVE FIXED-FREQUENCY STANDARD

A block diagram of the microwave fixed-frequency standard is shown in Figure 4. By mixing the outputs of this multiplier chain, coverage of the spectrum is provided at very closely spaced intervals. It is convenient to use 10 Mc intervals through 5,000 Mc; 50 Mc intervals through 25,000 Mc, and 250 Mc intervals through 40,000 Mc, as these are the strongest combinations. Since the standard signals occur at evenly spaced round numbers, errors in transcribing and plotting data are minimized. Also, from the evenly spaced frequencies, the equation of a calibration curve is easily calculated. The power available at the 10 and 50 Mc outputs of the chain is 5 watts, at the 250 and 3,000 Mc outputs; one watt, and at 9,000 Mc; twenty milliwatts. The tubes in the chain are operated well below maximum ratings to assure long life and stable operation. The klystron multipliers and amplifier are immersed in a temperature controlled oil bath for power output stability. Figure 5 shows a front view of the standard frequency multiplier chain. The lower drawer contains the multipliers from 100 Kc to 50 Mc and slides out to be easily accessible for maintenance and adjustment. The multiplier from 50 to 250 Mc and the 250 Mc amplifier are behind the hinged panel near the top.

The oil bath containing the klystrons, near the center of the rack, is also on drawer slides and pulls out to make connections to these tubes. The power supply at the bottom of the rack supplies the multipliers to 250 Mc and the one at the top supplies the klystrons. The complete unit takes only about four feet of panel space. Figure 6 is a rear view of the rack showing location of the temperature control unit for the oil bath and the power connections to the multiplier chains. A close up view of the oil bath and klystron tubes is shown in Figure 7.

5. METHODS OF USING THE MICROWAVE FREQUENCY STANDARD

Frequency meters sent in to NBS are calibrated as nearly as possible under the conditions of normal use. For instance, if the frequency meter has a built-in detector and indicator, then enough power is used to operate the indicating system. Or, if the meter can be used either as a transmission or a reaction meter, then both methods are checked to be sure there is no discrepancy between the two. Ambient room temperature where the calibrations are performed is held to $23^{\circ} \pm 2^{\circ}C$ and the relative humidity to 50 percent $\pm$ 2 per cent. Meters are left in the room for a sufficient time to reach equilibrium with the room conditions before calibration.

Figure 8 is a block diagram of the rf components used in a typical calibration. The standard frequencies are applied to a crystal diode mixer. The crystal is the necessary non-linear device needed to create all sum and difference combinations of the signals present. The desired signal is selected and all others rejected by the tunable transmission filter which has been previously calibrated. The frequency modulated local oscillator power is admitted to the converter crystal through a directional coupler where it is mixed with the standard signal. The intermediate frequency from the converter is fed to the spectrum analyzer and the matching sections are adjusted for maximum signal strength. The precision attenuators on either side of the meter to be calibrated are set to ten db each, to isolate the meter from the calibrating equipment and prevent reactive pulling of the meter. A photograph of a complete calibration set up is shown in Figure 9. The rack to the far right contains the local oscillator and power supply. The next rack contains the microwave fixed-frequency standard. The rf components are on the bench in the center and the spectrum analyzer is at the far left. A schematic and photograph of the mixer which combines the standard frequencies are shown in Figure 10. By means of the resonant circuits in series, the three standard signals are applied simultaneously to the crystal converter. By extending this method, additional desired frequencies may be added.

The frequency meter to be calibrated is set to resonance at each calibration frequency at least ten times. The spread of readings at a given frequency is then a measure of the backlash or other mechanical defects of the drive mechanism. This spread is included in the calibration report as the tolerance to which the readings are reproducible.

Although not included in a normal calibration, it is possible to measure the temperature coefficient of frequency of a cavity near room temperature and, also, the approximate "Q" of the cavity. The temperature coefficient is determined by observing the shift of resonant frequency at a fixed setting of the meter for different temperatures. The temperature of the cavity is monitored by a thermocouple junction attached to the frequency meter. The "Q" of the cavity can be measured by a system similar to that described in the M.I.T. Radiation Laboratory Series, Volume 11, pages 396 to 403.

6. METHODS OF DETECTING MICROWAVE STANDARD-FREQUENCY SIGNALS

Since the power of the harmonics used as standard-frequency signals is frequently as low as one microwatt, direct detection by means of a crystal diode and a sensitive current meter is usually impractical. In addition, the useful power at the detector is further reduced by a nominal insertion loss of 10 db for the transmission filter and 10 db each for the attenuators padding the meter being calibrated. The power available at the detector is then about 0.001 microwatt. Therefore, when a frequency meter with a built-in crystal detector is to be calibrated, a higher power cw oscillator must be used and adjusted to the frequency of the standard signal. By amplifying and observing the beat note between the standard signal and a small portion of the oscillator output, the oscillator may be adjusted to the same frequency as the standard-frequency signal with precisions decreased a minimum of one order of magnitude. The remainder of the oscillator's power is then enough to permit the crystal current from the detector to be monitored with a microammeter.

In cases where the standard signal can be passed through the meter to be calibrated, a sensitive receiver may be used to detect the signal. In the frequency range 300 to 750 Mc a double superheterodyne panoramic receiver is used. Above 750 Mc a sensitive spectrum analyzer is used to detect the signal.

Direct reading local oscillators of the external cavity reflex klystron type are available from 750 to 11,000 Mc. Above 11,000 Mc internal cavity reflex klystrons are mounted directly on the waveguide test set up to provide local oscillator power.

Since the local oscillator power is much more than that of the standard signal, the height of the pulse displayed is directly proportional to the power of the standard signal. The frequency meter being calibrated may then be tuned to resonance by observing the pulse height on the cathode ray display tube.

The spectrum analyzer has a voltage gain of 160 db and can detect a standard microwave signal as low as 10^{-13} watt.

7. MICROWAVE COMPONENTS AND TECHNIQUES UNDER DEVELOPMENT

Development work is in progress at the National Bureau of Standards to improve the calibration techniques at frequencies above 40,000 Mc. To date, industrial engineering efforts in this range have been limited and although many of the components can be scaled from lower frequency equipments, the lower frequency harmonic generators and crystal detectors already have parts with as small a dimensional tolerance as present techniques permit. The engineering effort at the Bureau is being concentrated on three major items for frequencies above 40,000 Mc. The first is the development of crystal harmonic generators. The second is the development of crystal detectors--mixer crystals where local oscillator power is adequate; crystal video detectors where the local oscillator power is less than 1 milliwatt. The third is development of secondary frequency standards. The simple-mode resonant cavity design so convenient at lower frequencies suffers reduction in Q and reduction in dimensional accuracy. The small signal levels usually available above 40,000 Mc create the need for a passive secondary standard of frequency that requires very little power. A waveguide-contained interferometer design shows promise as such a secondary standard of frequency.

A technique is being worked out for mixing an interpolation oscillator signal along with the outputs of the microwave fixed-frequency standard to improve the continuous frequency coverage.

The technique of amplitude modulating a standard frequency signal in a magnetic attenuator is being evaluated.

The future program of the National Bureau of Standards Microwave Frequency Standards Group includes expansion of the facilities available for calibration by extension of the present 300 to 75,000 Mc range upward to 100,000 Mc and higher. An attempt will be made to simplify high precision frequency measurements by providing higher power in the standard signals at microwave frequencies. The present development programs of NBS and others on atomic and molecular spectrum lines for use as frequency and time standards give an absolute standard independent of astronomical methods.[11,12,13,14,15] Although these programs are still in process, results indicate that greater absolute accuracies can be achieved by such a standard, particularly by atomic beam techniques. Clocks using ammonia and oxygen, employing gas absorption techniques are under development and promise accuracies of the order of that obtained by astronomical methods.[16,17] Problems of long running and reliability are still severe. However, these problems are reduced for standard frequency applications alone and in this area the beam techniques already indicate superior results. On the basis of recent tests, the ammonia clock (the rack shown to the right in Figure 3) as a standard is several orders of magnitude better than current secondary standards, and about equal to the precision of long distance radio links to WWV standard signals where the skywave is limited in accuracy by shifts in the height of the ionosphere.[18,19]

8. CONCLUSIONS

The radio spectrum is becoming crowded and the best utilization of the microwave spectrum can be achieved by relying on secondary microwave frequency standards for alignment of components and some of the high power transmitters. The closer tolerances on the match of frequency sensitive components are also creating a demand for calibrated secondary standards. The calibration service has been effective in coordinating the secondary standards throughout the laboratories of the United States and in the evaluation of new types of secondary standards.

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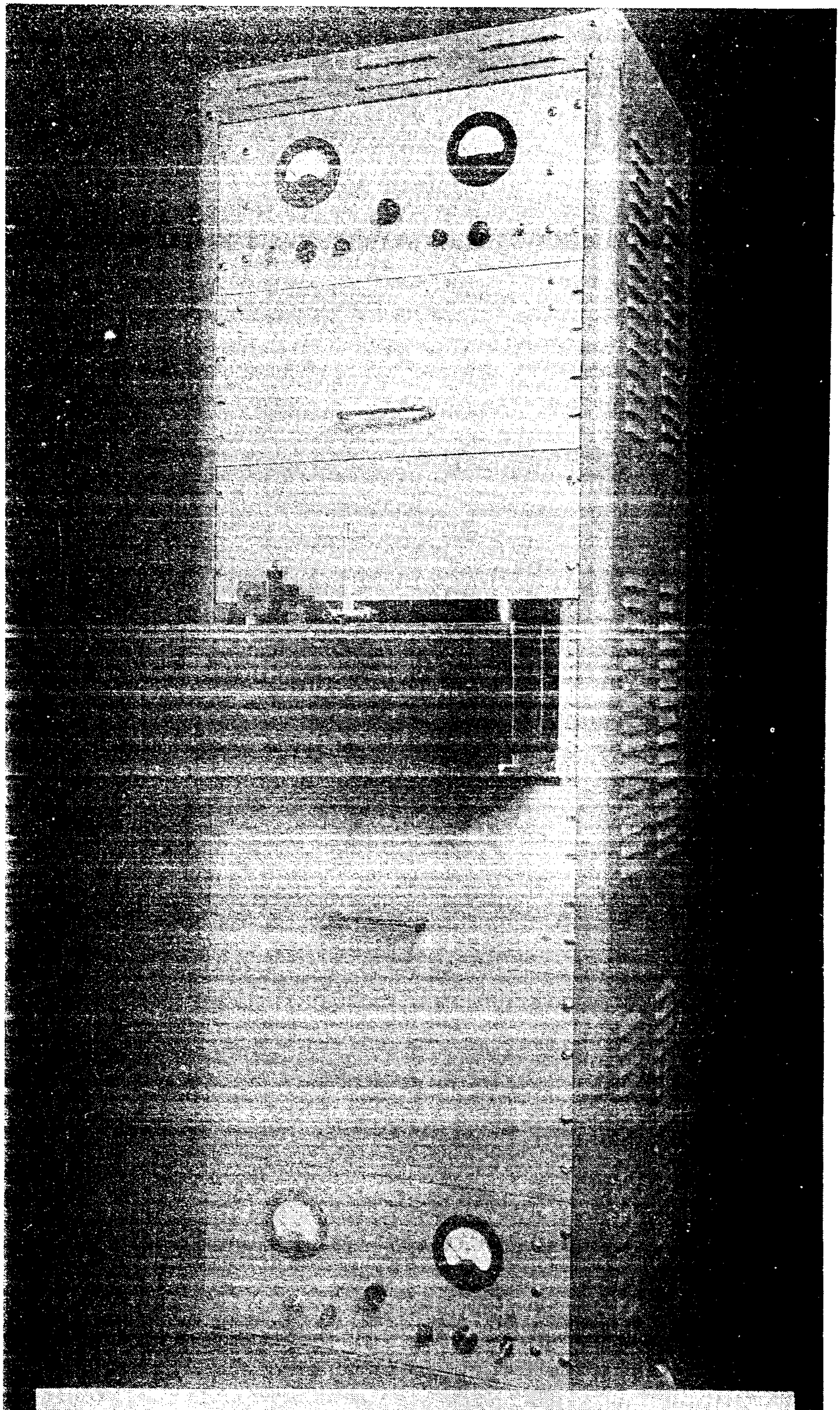


Frontispiece. The Fixed-Frequency Microwave Standard

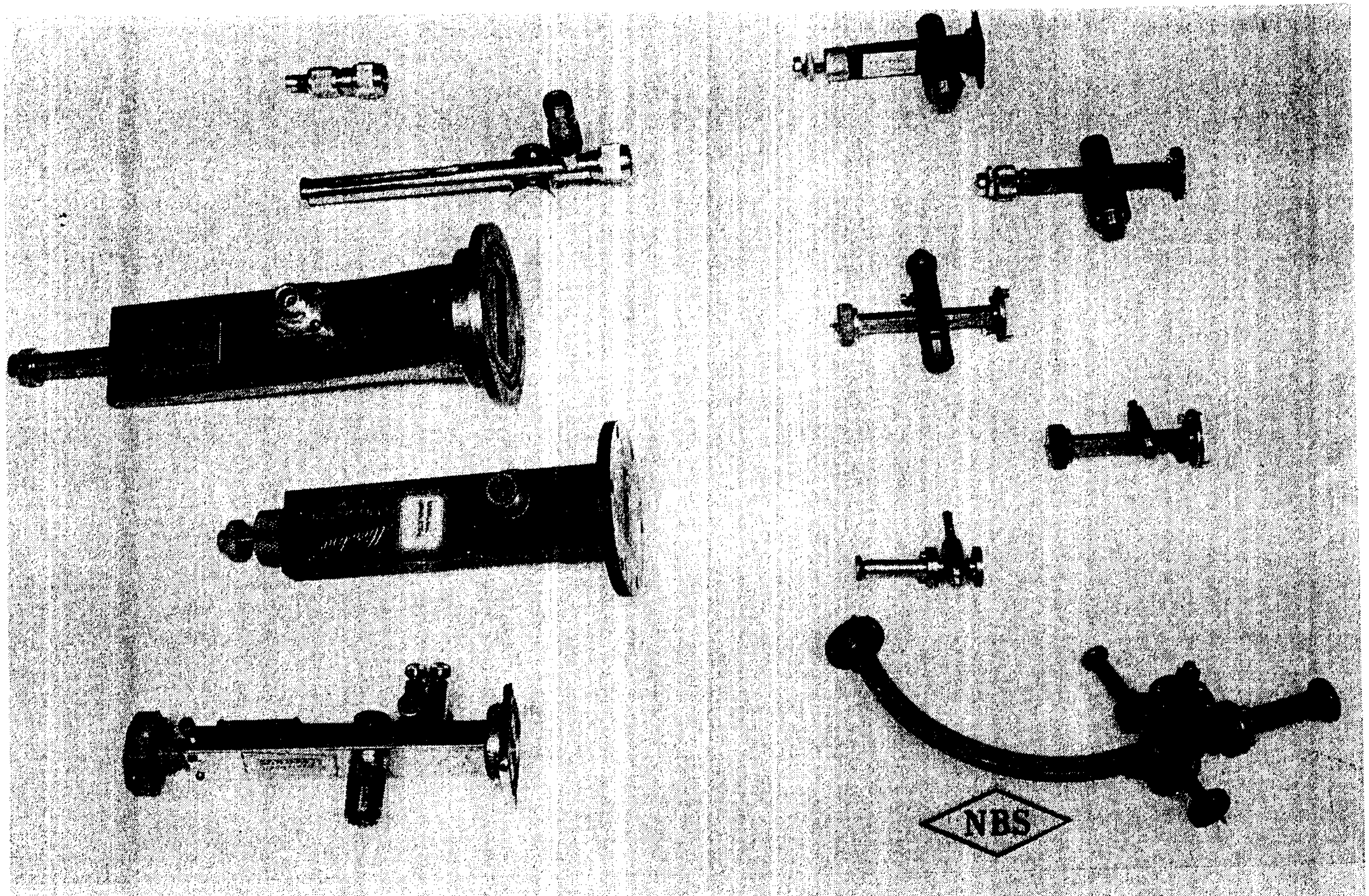
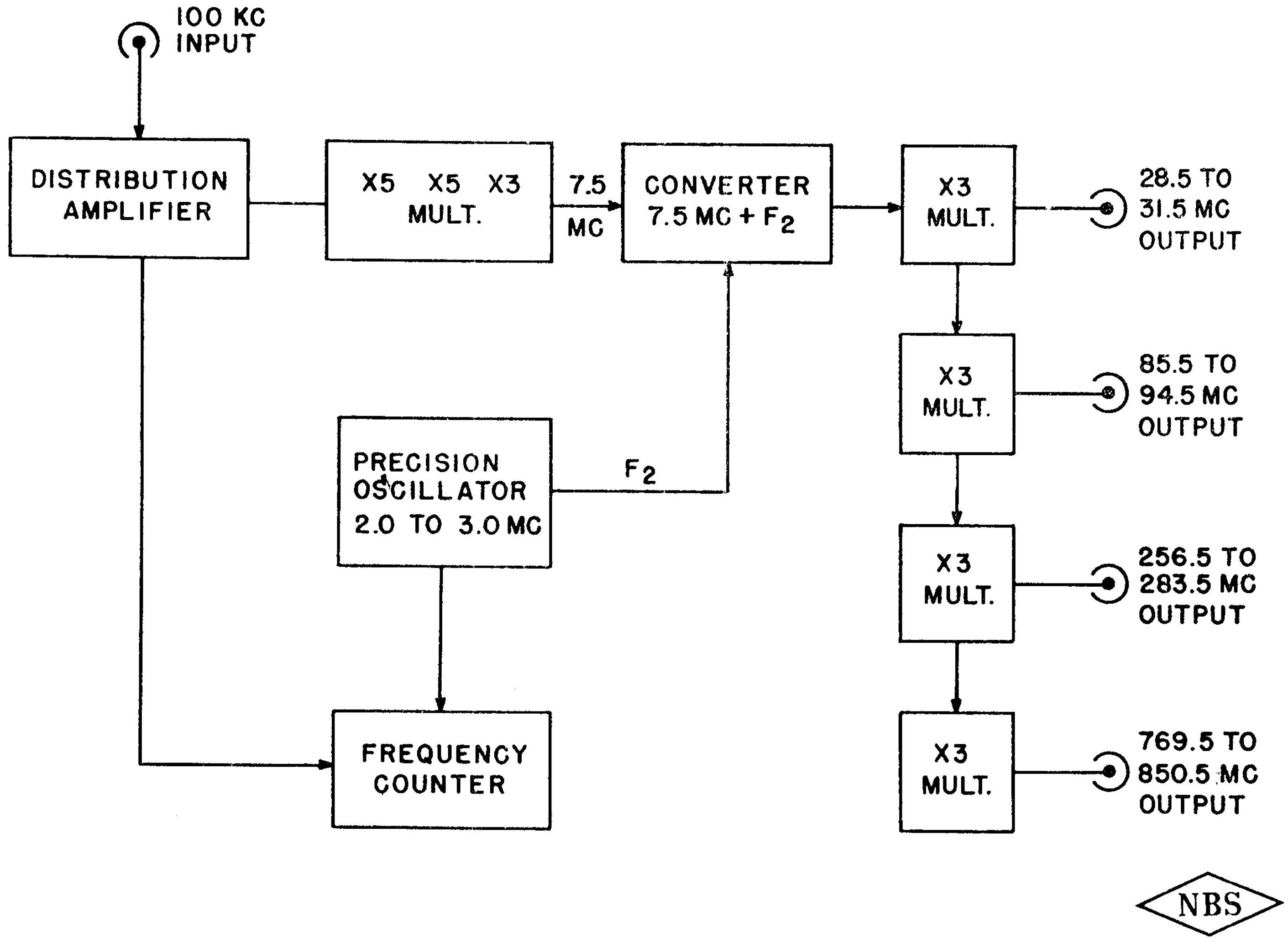


Figure 1. Harmonic generators for the range from 300 Mc to 75,000 Mc.



BLOCK DIAGRAM OF MICROWAVE
ADJUSTABLE-FREQUENCY STANDARD

Figure 2.

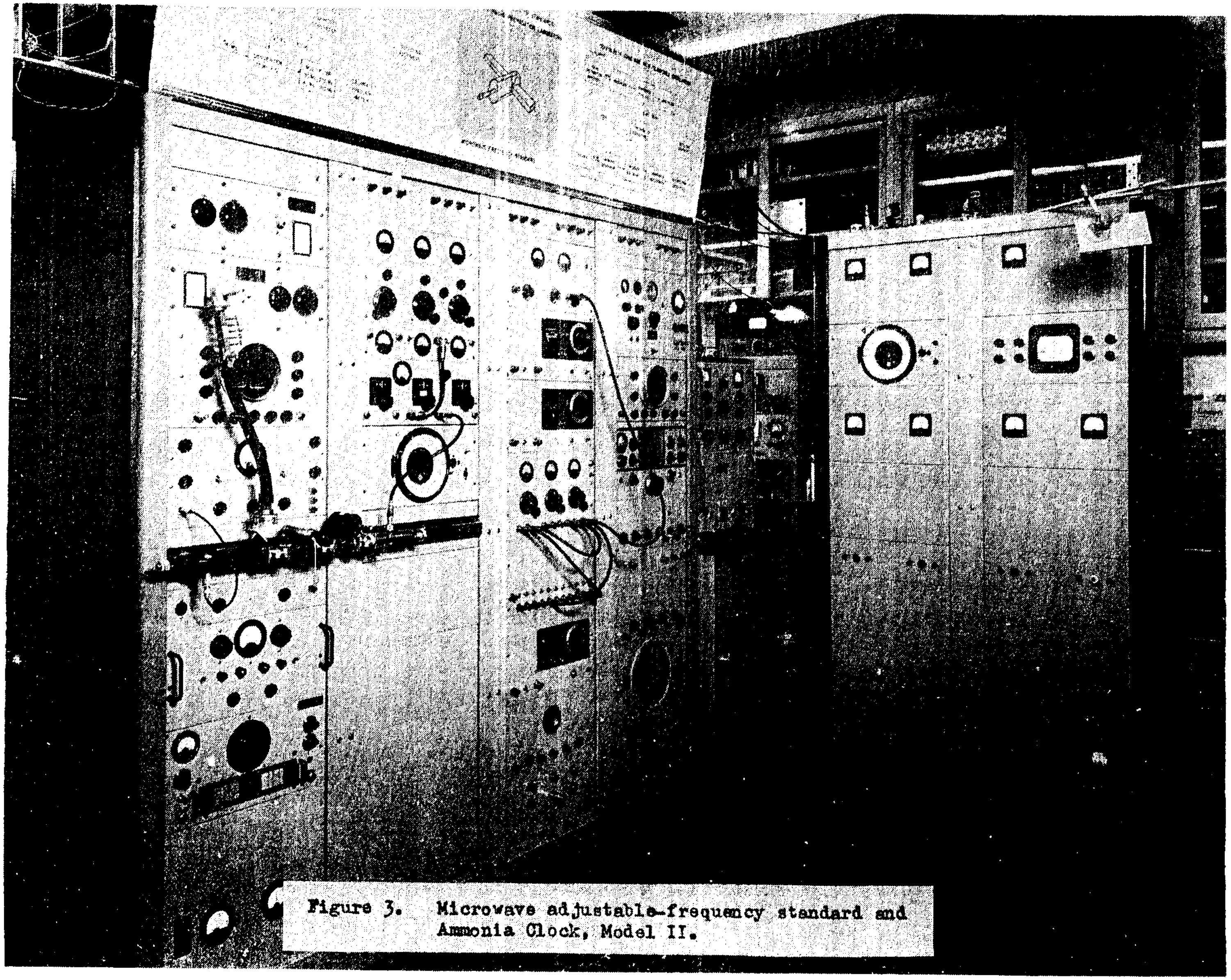
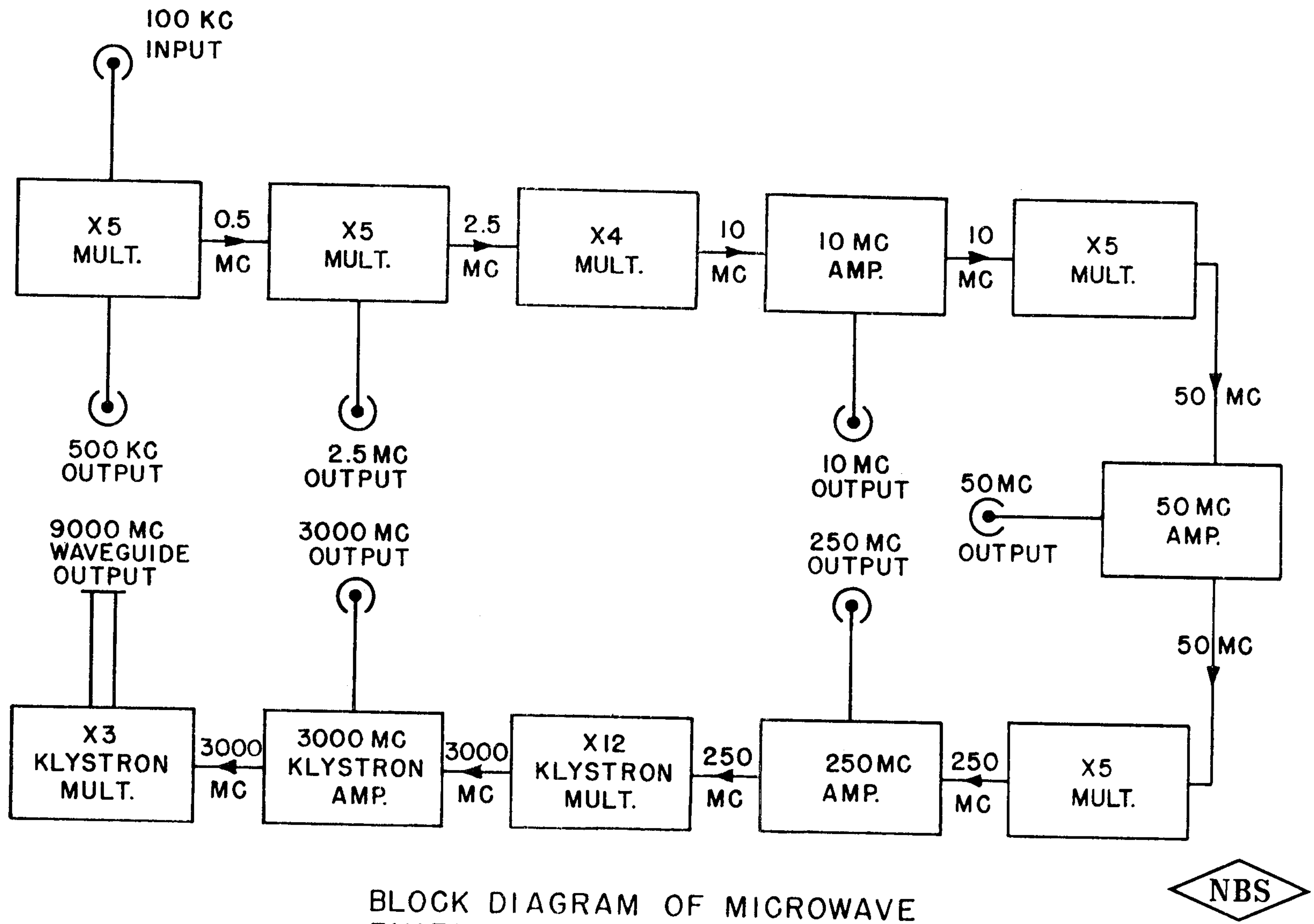


Figure 3. Microwave adjustable-frequency standard and Ammonia Clock, Model II.



BLOCK DIAGRAM OF MICROWAVE FIXED-FREQUENCY STANDARD

Figure 4.

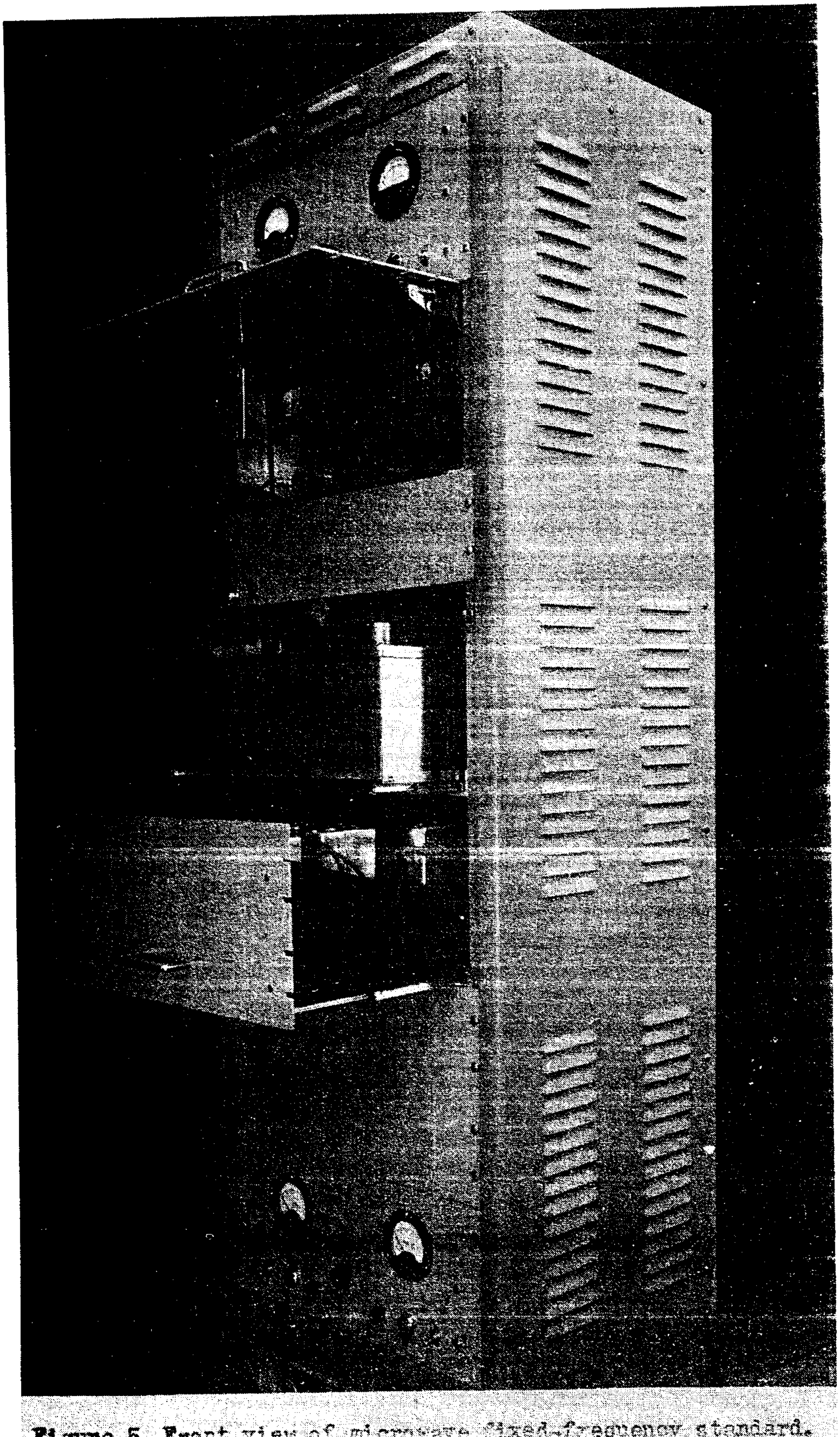


Figure 5. Front view of microwave fixed-frequency standard.

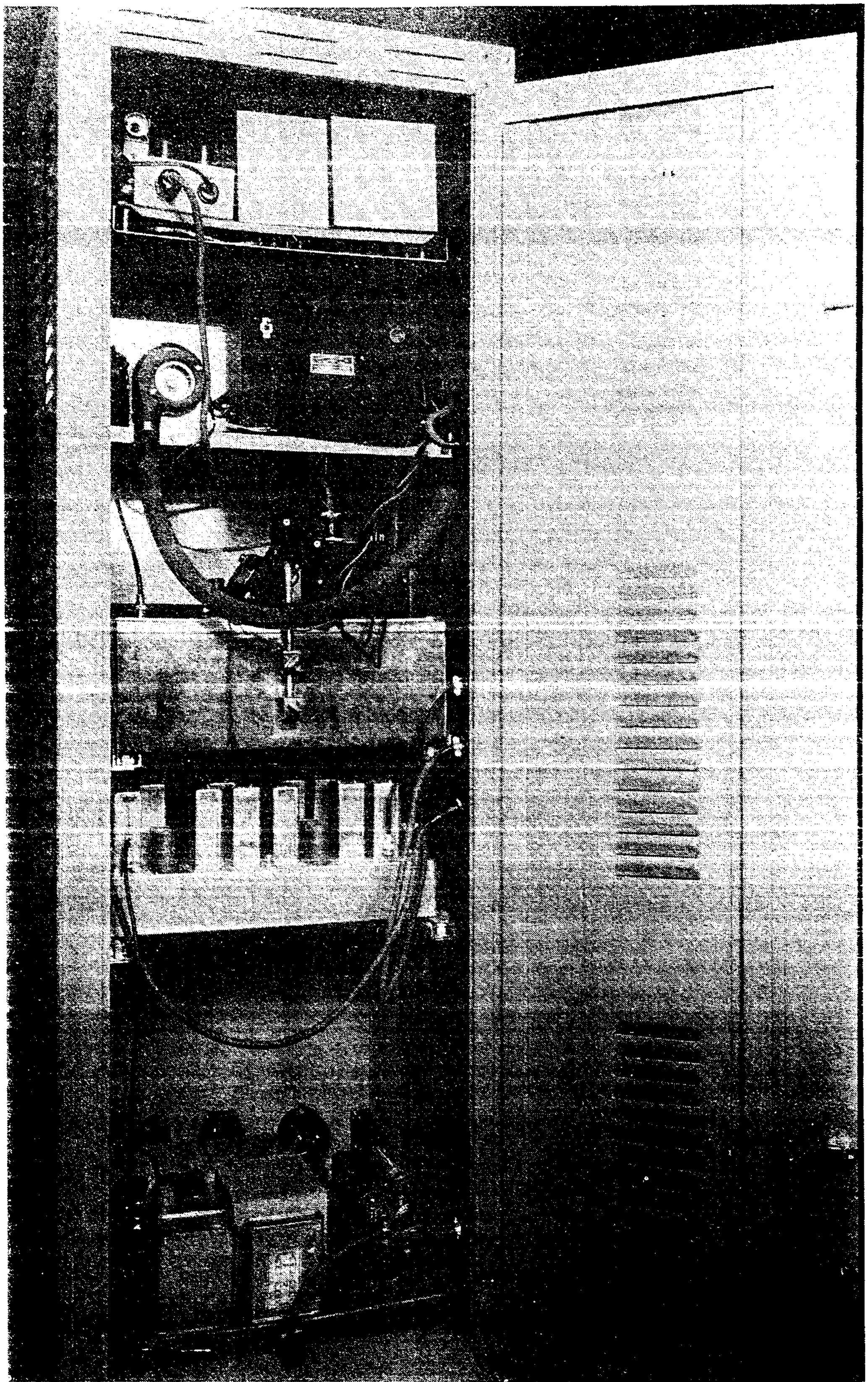


Figure 6. Rear view of microwave fixed-frequency standard.

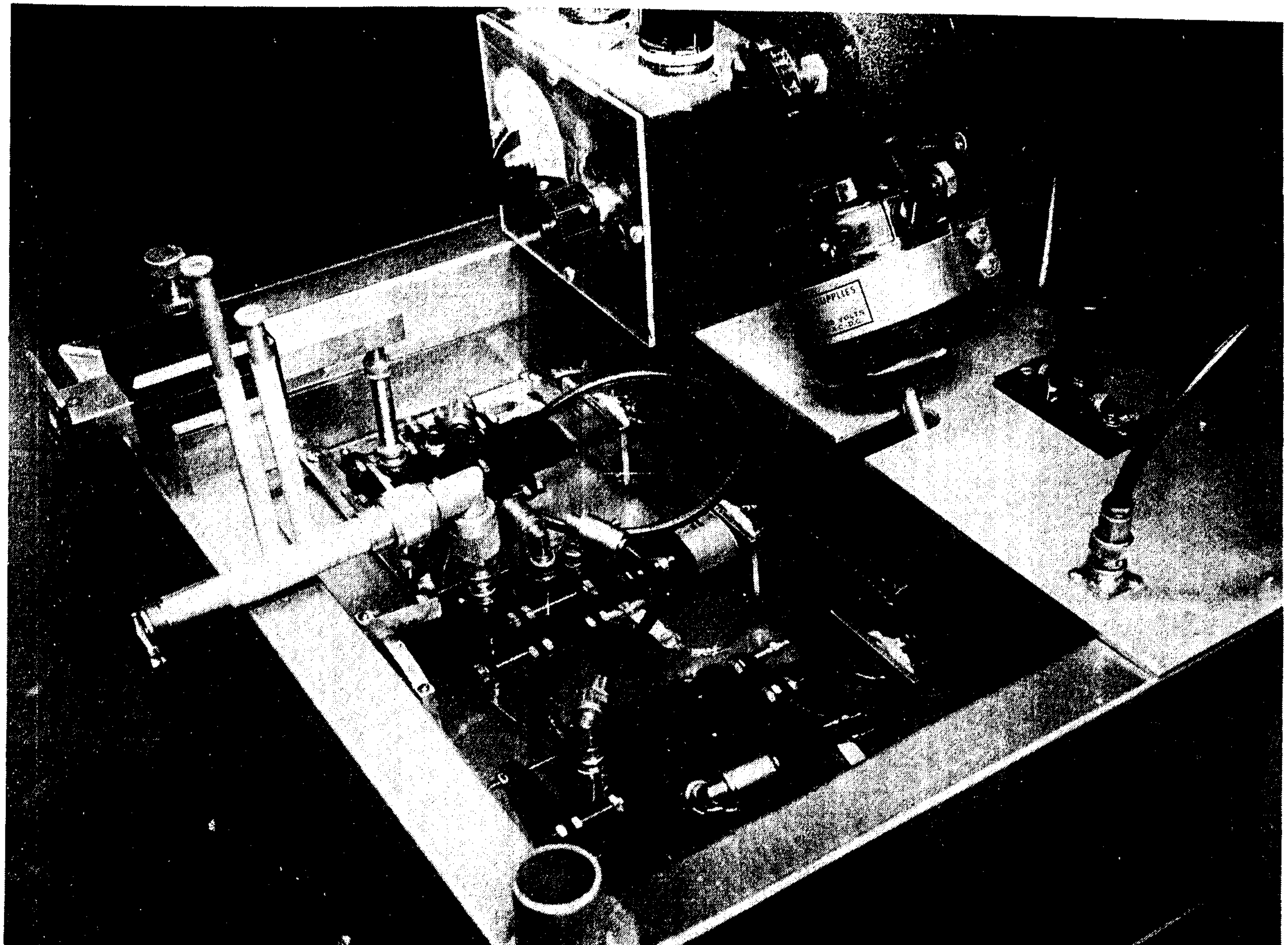
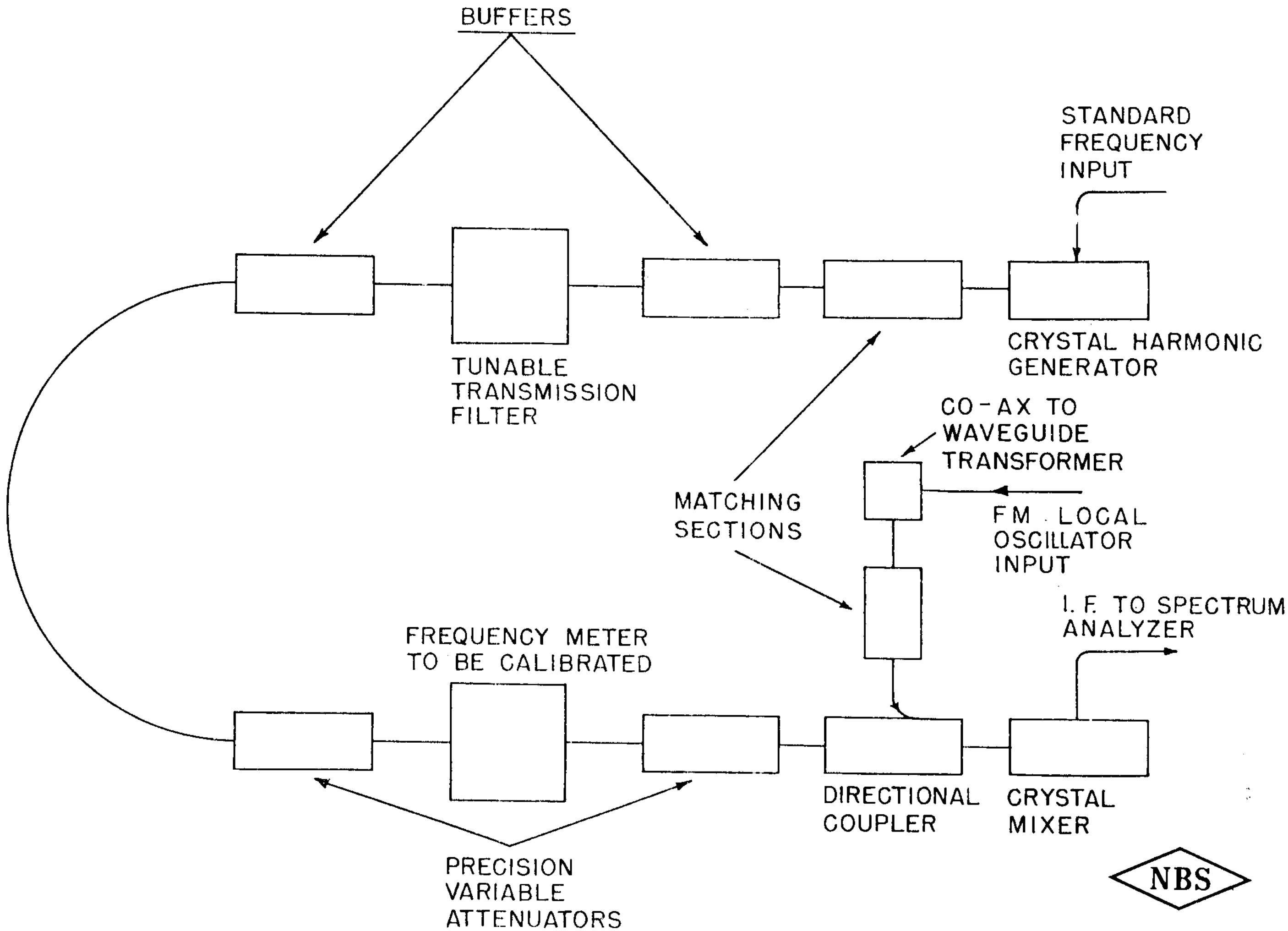


Figure 7. Temperature controlled oil bath for klystrons in microwave fixed-frequency standard.



BLOCK DIAGRAM OF R F COMPONENTS USED IN FREQUENCY CALIBRATION

Figure 8.

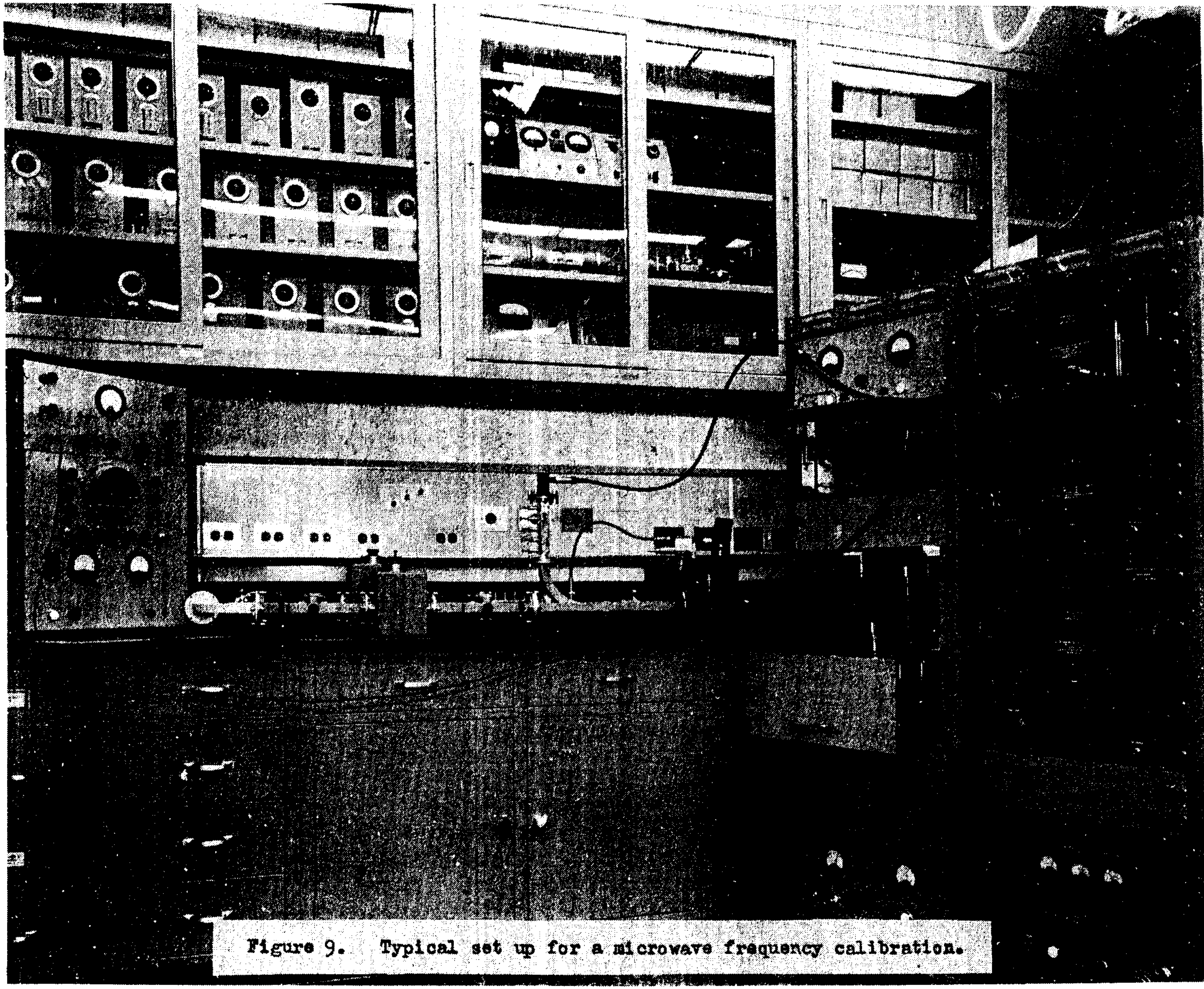


Figure 9. Typical set up for a microwave frequency calibration.

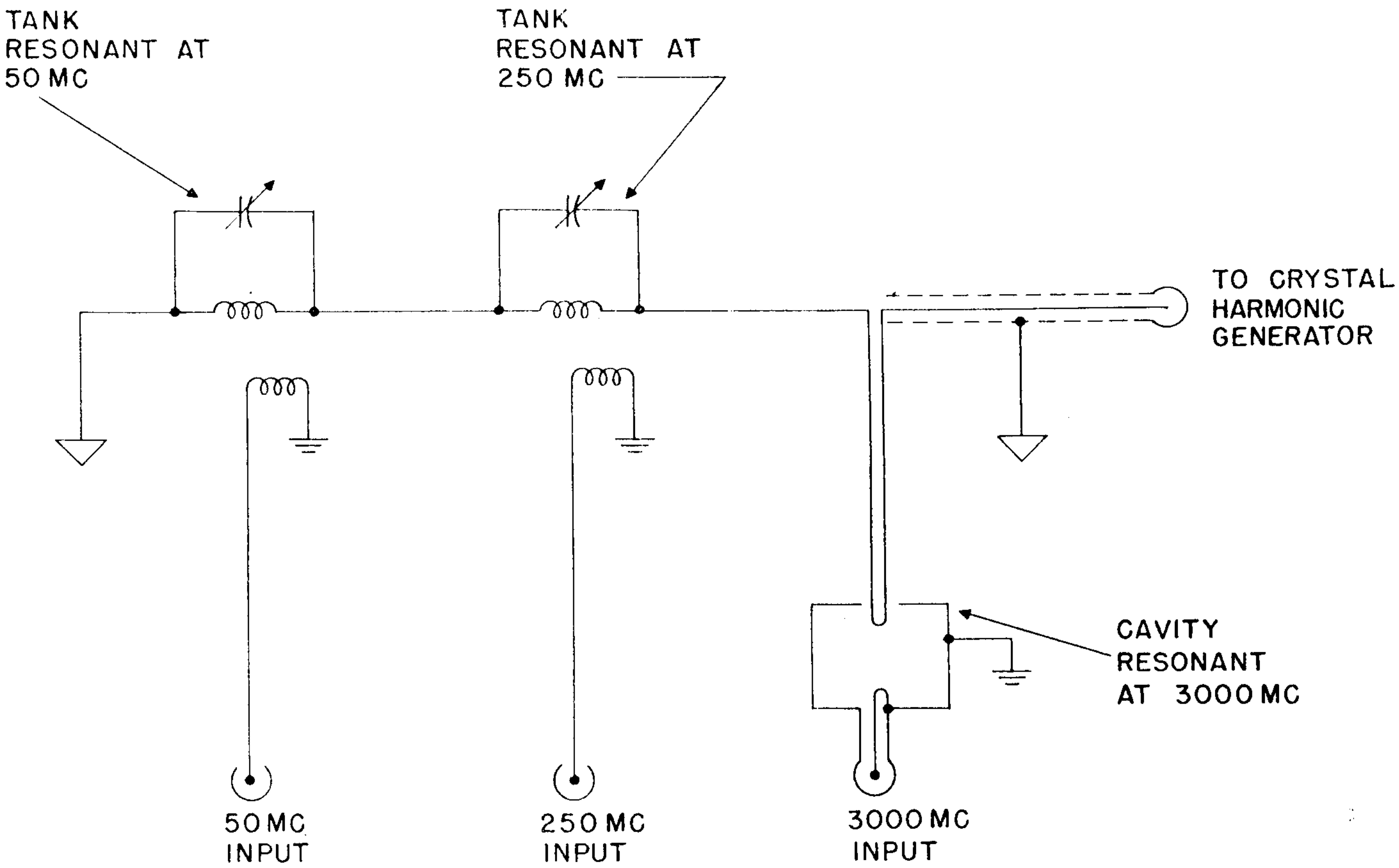


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Figure 10a. Schematic of mixer for combining standard frequencies

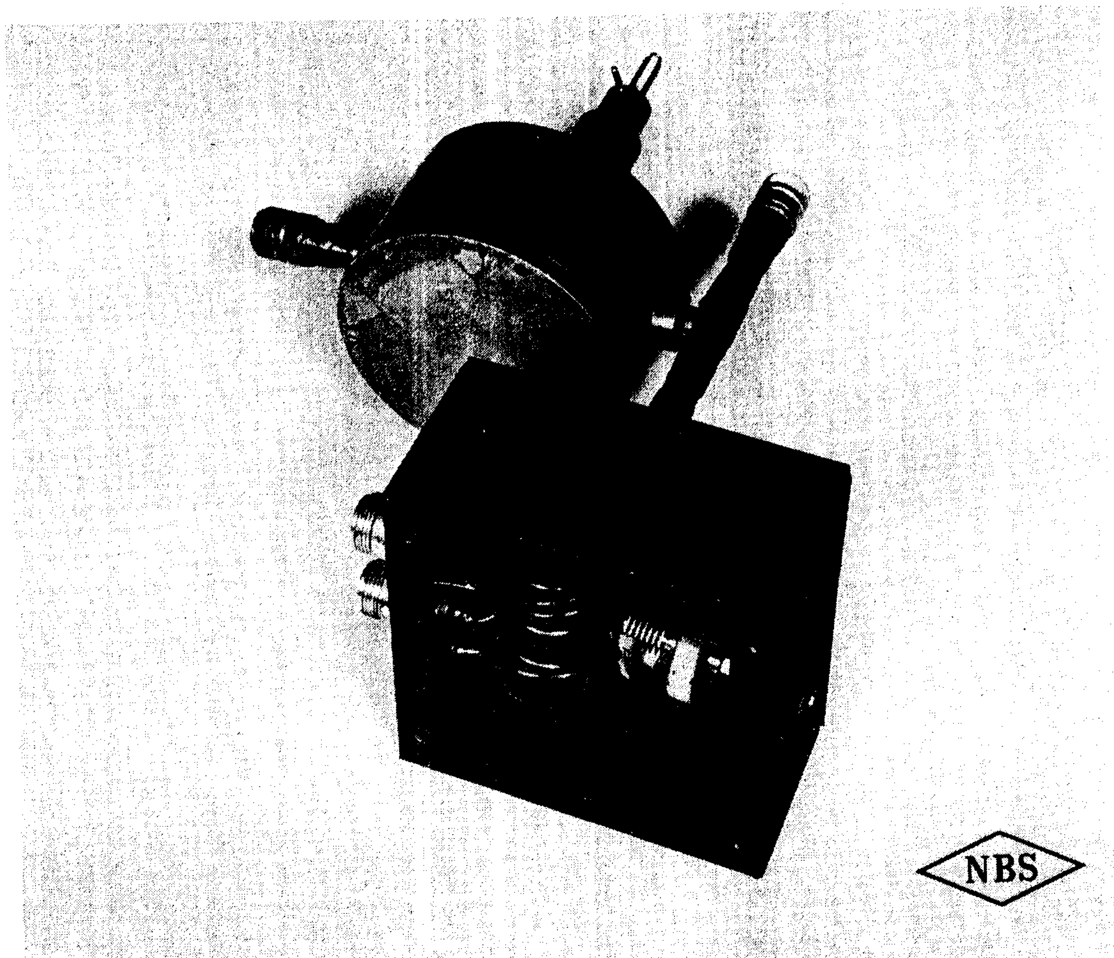

Figure 10b. Mixer for combining standard frequencies.