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ACCURATE PHASE LENGTH MEASUREMENTS OF LARGE MICROWAVE NETWORKS*

J. Weaver[†] and R. Alvarez

Stanford Linear Accelerator Center
Stanford University, Stanford, California

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[†]Presently with W. W. Hansen Laboratories, Stanford University, Stanford, California.

ABSTRACT

The Stanford two-mile linear accelerator uses 240 single-input-port, four output-port, S-band, rectangular-waveguide networks to feed rf energy sixty to seventy feet from the klystrons above ground to ten-foot-long, disc-loaded circular-waveguide, accelerator sections below ground. During installation it is necessary to permanently adjust the phase lengths of the four network branches to be within ± 4.5 electrical degrees of the design lengths for rf wave and electron beam synchronization.

A modulated reflection phase length comparison method is used, whereby a small signal is sent into each branch and reflected, in turn, by a diode switch, which is turned on and off at a 1kHz rate. A null occurs in the amplitude modulation of the sum of a large reference signal and the small reflected signal when the two signals are nearly in phase quadrature. The reflectors are placed so that the network branches are properly adjusted when the nulls from all branches occur for the same setting of a variable phase shifter in the measurement line.

Small mismatches and multiple power divisions do not affect the accuracy of this method. Frequency, temperature and air pressure are the main environmental conditions affecting the measurement and are discussed along with the design of the reflecting diode switch, which is mounted in a vacuum-sealed waveguide flange.

I. INTRODUCTION

Often the accurate measurement of electrical phase lengths is necessary in the design of microwave circuits. For numerous components and devices a short length of transmission line is needed to act as a transformer to match two impedances. In other cases, where the load and the generator are matched already to the characteristic impedance of the transmission line, but the generator feeds several output ports, it may be important that the signals arrive at the respective ports with specific time delays or phase relationships. The system described below is designed to measure this latter type of network.

The method used to make an electrical phase length measurement depends upon the type of network. Relative or comparison phase length measurements generally are easier to make than absolute phase length measurements, which may require detailed knowledge of the device's phase versus frequency response. Thus, the phase length usually is determined by comparison with a similar, known or reference phase length in conjunction with an accurately, calibrated, variable phase shifter.

The device to be measured may be inserted into the measurement circuit, so that the test signal either is transmitted through the device, or sent through the device and reflected back through it by a reflector on the output. A reflection method measures twice the length, and thus half-cycle phase length differences appear as full-cycle phase shifts. This phase ambiguity in large networks, with uncertain phase-frequency characteristics, is not resolvable simply by measuring the phase length at several frequencies. A transmission phase measurement method for a large network usually requires that a long, phase-stable, return path be provided from the output port of the network back to the phase measurement system. Often with both methods, effects due to small, undesired, CW reflections and unequal, circuit attenuation can be minimized by modulating the signal. A more complete discussion of various phase length measuring techniques is given by Lacy, and others.[1-7]

The problem of adjusting the phase length of the 240 rectangular waveguide feed networks for Stanford's two-mile linear accelerator was solved by using a modulated reflection method,[8] similar to one suggested by Schaeffer[2] and later further developed and used by Swarup and Yang[9] to adjust a radio astronomy antenna array. The accelerator utilizes a high-power, S-band, rectangular-waveguide network to feed rf energy from each 25 megawatt klystron amplifier through 25 feet of earth shielding to four, independently fed and terminated, 10 foot, disc-loaded, circular-waveguide, accelerator sections (Fig. 1). In operation an rf wave appears to move along the entire accelerator in a single coherent wave with a phase velocity equal to c. This condition requires that each accelerator section have an rf phase velocity equal to c at the operating frequency, 2856 MHz, and that the rf wave entering each section be phased correctly with respect to the bunched electron beam. Each klystron is individually phased by an automatic system[10] to obtain the correct phase relationship between the bunched beam and the wave in one particular accelerator section driven by that klystron. Thus, the high power waveguide feed network must be permanently adjusted so that when the wave is phased correctly with respect to the beam in that one accelerator section, it is phased correctly in the other three sections driven by that same klystron. Since the accelerator rf input ports are spaced by an integral number of wavelengths (29), the waveguide network branches must be adjusted to be equal in phase length, or to differ by only an integral number of wavelengths.

The modulated reflection method for phase adjustment uses an individually controlled reflector (modulator flange) at each of the four output ports. A 2856 MHz cw signal is fed to the input port of the waveguide network, then one reflector at a time is switched at a 1 kHz rate, and each return signal is compared in quadrature with a much larger unmodulated reference signal. The resultant signal will exhibit no 1kHz amplitude modulation when the reference signal and the carrier of the modulated reflected signal are out of phase by ninety degrees. Meanwhile, the diodes in the other three modulator flanges are not switched, but dc biased to cause little reflection. This allows comparison of the phase lengths of the four branches, subject to the half-cycle ambiguity of the reflection method. The half-cycle ambiguity then is resolved by a transmission phase measurement, which uses the modulator flanges as coax-to-waveguide adapters and uses a long coaxial cable as the return path to the input port of the waveguide network.

The particular problems encountered with the networks (see Fig. 1) are: its large physical size, its 6 dB of power division per branch, and numerous, small mismatches of undetermined phase. The great length of the network branches requires that the phase-length dependent parameters (temperature, frequency, and dimensional tolerances) be stringently controlled. However, some of the temperature dependent effects tend to cancel, as they are nearly the same for all the branches of a network. Unequal attenuation and random, small, network reflections produce only second order phase measurement errors with the modulated reflection method.

II. DESCRIPTION OF THE MEASUREMENT SYSTEM

The phase length measurement system consists of four modulator flanges (Fig. 2), connecting cables and the phasing machine console (Fig. 3). The circuit, including the network under measurement, is shown in Fig. 4. A vector diagram showing the relationship between the pertinent signals at the detector and the equations for those signals are given in Fig. 5. Equations (1), (2) and (3) give the expressions for the cw reference signal, v_r, the square wave modulated reflected signal, v_m, and the resulting sum signal, v_s, respectively. The microwave frequency is ω_c, and the reflector is switched at ω_m. The reference phase length from the signal generator to the detector is η, and the phase length from the generator through one branch of the network to the modulator flange and back to the detector is θ. The modulation index is m. Equation (4) gives the quadrature null conditions.

Two things should be pointed out about Eq. (4). First, the null conditions are independent of the type of amplitude detection (linear, square law, etc.), and secondly, the phase length θ varies as twice the length of a branch. Thus, the phase shifter in Fig. 4 can be adjusted so that η is in quadrature with θ for any network branch, if its length is any multiple of quarter wavelengths long. The quarter-cycle ambiguity can be resolved by noting (see the vector diagram of Fig. 5) that when θ is increased by the phase shifter the resulting vector, v_s, increases in amplitude if $(\theta - \eta) \approx 270^{\circ} \phi$ and decreases when $(\theta - \eta) \approx 90^{\circ} \phi$. Whether v_s increases or decreases is easily determined by synchronous detection; that is, by triggering the oscilloscope (Fig. 4) with a 1 kHz signal from the modulator power supply and observing whether the 1 kHz amplitude modulation of v_s (at the crystal detector) is of the same phase as each of the four modulator flanges is energized in turn.

The remaining half-cycle ambiguity is resolved by a transmission phase measurement, for which a 75-foot coaxial cable serves as the return path from each modulator flange, one at a time, to the phasing machine console. The phase length instability of the coaxial cable prevents the transmission measurement from being accurate to better than $10^{o}\phi$. A reference signal and the transmitted signal are fed into the opposite ends of a standing wave detector, and the sliding probe indicates any shift in null position from branch to branch. By referring to Fig. 4 the signal paths may be traced for the three functions of the phasing machine console: coarse phase measurement (transmission method), fine phase measurement (modulated reflection method) and network input VSWR measurement.

For coarse phase measurement the coaxial switches are set to the coarse phase position, and the waveguide switch is rotated to connect the standing wave detector to the waveguide network. The modulator power supply performs three functions: it 1 kHz square wave modulates the signal from the 2856 MHz signal generator, it reverse biases the appropriate modulator flange through the dc isolation tee, and it forward biases the other three modulator flanges directly. A frequency counter and power meter monitor the signal before it enters the 1 kHz modulator. A 43dB directional coupler shunts a small reference signal through an isolator into the standing wave detector. Most of the signal passes through the 75-foot coaxial cable to a dc isolation tee and through the reverse biased modulator (now serving as a coax-to-waveguide adapter) to one branch of the waveguide network. The signal then passes through the waveguide network, through a variable attenuator, and into one end of the standing wave detector. The variable attenuator is used to equalize the amplitudes of the transmitted signal and the oppositely-traveling reference signal, and thus to produce a sharp null in the standing wave pattern. Comparing the positions of the nulls for the four branches gives a direct comparison of the phase length differences.

For fine phase measurements the coaxial switches are put in the fine phase position, and the waveguide switch is rotated to connect the main waveguide circuit to the network. The modulator power supply is used to synchronize the oscilloscope, to switch one of the modulator flanges at a 1 kHz rate, and to forward-bias the others. A cw signal enters the waveguide and most of it passes directly to a magic tee and detector; this is the reference signal, v_r. The first waveguide directional coupler sends one tenth of the initial signal through a precision, calibrated, dielectric-slab, phase shifter and a waveguide switch to the waveguide network. The modulator flanges at the end of the network are switched, one at a time; so that a small amplitude modulated signal is reflected back into the waveguide switch, after which a second waveguide directional coupler sends one hundredth of the signal to the magic tee and the detector. At the detector the modulated, reflected signal, v_m, is about 52 dB below the reference signal v_r. The phase shifter is adjusted to produce a null in the 1 kHz amplitude modulation of the sum signal, v_s. The differences in the phase shifter readings for the four branches of the network are direct measures of the phase length differences. A standing wave indicator conveniently doubles as a 1 kHz tuned amplifier for the detected amplitude modulation of the sum signal, which is then displayed on an oscilloscope. The oscilloscope indicates the null condition and also, by being synchronized by the modulator power supply, indicates the relative sign of the 1 kHz modulation term and thus removes the quarter-cycle ambiguity associated with the modulated reflection method. The standing wave detector also is used to measure the input VSWR to the network. An additional waveguide switch allows mounting of a reference modulator flange, which can be used to calibrate a set of four flanges relative to each other and to monitor any drift of the phasing machine.

The modulator flange (Fig. 2) consists of a diode switch mounted in a special, stainless-steel, vacuum sealing, S-band waveguide flange. The point contact germanium diode is spring loaded on the end of a post across the waveguide. Two adjustable tuning screws in the plane of the diode are used for matching. The tuning screws and the diode post, which connects to the center conductor of a TNC fitting on the flange circumference, are vacuum sealed with teflon O-rings. Thin gold plating on top of copper plating improves the calibration accuracy and the shelf life of the stainless steel flanges. When the flange is properly tuned, reverse biasing the diode creates a large shunt admittance across the waveguide, which results in ninety to ninety-five percent voltage reflection. Forward biasing creates a small shunt admittance, which results in ten to fifteen percent voltage reflection.[11] The tuning screws are adjusted so that the phase of the sum of the small and large reflections are the same in all four modulators. The magnitude of the reflections determines the modulation index m, and the phase determines the modulator flange calibration value. Since the diodes exhibit a non-linear phase versus voltage characteristic, square wave modulation makes for easier understanding and analysis of the circuit. The modulator power supply switches the diode bias signal at a 1 kHz rate from -20v to +100 ma. When the diode is reverse biased, the modulator flange serves as a coax-to-waveguide adapter with stable phase characteristics and a transmission loss of about 20 dB.

Between the diode support post and the flange body, there is a capacitive reactance of about 1.4 ohms at 2856 MHz, which provides some isolation between the bias circuitry and the microwave reflector circuitry. Since the modulator flange is primarily a precision reflector, and only incidently a coax-to-waveguide adapter, the 20 dB transmission loss is preferable to less isolation. Frequent recalibrations locate the position of the equivalent plane of reflection to better than $\pm 0.3^{\circ}\ \phi$. The major source of calibration error is the small movement of the internal parts of the flange modulator during its installation, which requires a small amount of bowing of the flange to make a satisfactory vacuum and rf seal. The critical parts are machined to tolerances of $\pm$ 0.001 inch. The modulator flange is definitely the most critical component of the system.

Before the waveguide components are assembled, they are matched to a VSWR of better than 1.05 and isolators were used in the appropriate places. Two sections of flexible waveguide are used (Fig. 3) between the waveguide switch and the network and the waveguide switch and the standing wave detector for greater ease in connecting to a network. In the case of the standing wave detector, a three screw tuner was used to match the flexible waveguides and the waveguide switch. The flexible waveguide does not affect significantly the accuracy of the modulated reflection method. Ground loops, frequency drift, temperature fluctuations, and modulator calibration accuracy are the major sources of phase adjustment error. If this type of system is to be used over a range of frequencies and for absolute phase length measurements a good deal of care would be required in its design and calibration. However, many of the mismatches and component phase characteristics are not detrimental when the system is operated at a single frequency and as a null comparison meter.

III. RESULTS AND LIMITATIONS OF THE MEASUREMENTS

Phase length measurements and adjustmets were made on 240 networks. The branches of any single network are from 59 to 70 feet long (118 to 140 guide wavelengths), and there are seven, vacuum tight, copper gasket joints along each branch. The waveguide components were tuned for minimum VSWR before installation, but is was necessary to adjust the phase of the networks after its final installation because of their great length, their numerous joints, and their sensitivity to temperature and vacuum conditions. The ten-foot accelerator sections were included between the modulator flanges and the output ports of the waveguide network (Fig. 4), so the network would not have to be moved or connected after its adjustment. Including the accelerator sections in the measurement was possible since their phase lengths were adjusted to within $\pm 2.5^{\circ}\ \phi$ before installation. The biggest problem was maintaining their temperature. Figure 6 shows the phase length dependency of a network and an accelerator section. The phase length of an accelerator section is seen to be eight to ten times more sensitive to temperature and frequency changes than a waveguide network branch. A water heating system that sets the accelerator sections and waveguide network temperatures nominally at 113°F is capable of maintaining a temperature difference between network branches of less than 0.75°F and between accelerator sections of less than 0.2°F for conditions of no rf power, such as during phase measurement. Phase length stability under accelerator operating conditions is more complex, and is treated elsewhere.[12]

The measurement frequency is monitored with a frequency counter and maintained within 500 Hz of 2856 MHz. The network and accelerator sections are evacuated to less than 25×10^{-3} (torr).

At this internal pressure,changes in internal pressure do not affect appreciably the phase length, either by change in dielectric constant or by elastic deformation of the waveguide walls. However, elastic deformation, due to changes in external atmospheric (barometric) pressure, can cause measurable changes in phase length. These changes will be less than 0.014 $(^{o}\phi)\cdot(\mathrm{ft})^{-1}$ for 5% changes in barometric pressure. It is interesting to note, too, that the total effect of evacuating the system from 760 torr of dry N_2 to less than 25×10^{-3} torr is -0.68 $(^{o}\phi)\cdot(\mathrm{ft})^{-1}$ for the rectangular waveguide and -280 $(^{o}\phi)$ for the ten foot accelerator section.[12]

The total attenuation of the reflected signal, v_m, is about 52 dB greater than the reference signal, v_r; therefore, the quadrature null condition of Eq. (4) results in a $(\theta - \eta)$ of not exactly 90 $(^{o}\phi)$ or 270 $(^{o}\phi)$, but 90.07 $(^{o}\phi)$ or 269.93 $(^{o}\phi)$. Thus, small variations in attenuation of less than a dB from branch to branch cause less than 0.01 $(^{o}\phi)$ error. The waveguide network input VSWR after tuning is less than 1.2; this contributes a negligible error to this kind of modulated-reflection, null-comparison method. The actual phase adjustments are performed by permanently indenting the waveguide walls with special C-clamps with twelve-inch jaws. Smooth indentations over a length of several feet easily produce phase shifts up to the usually maximum variation between branches of 60 $(^{o}\phi)$. A few networks were out of adjustment by almost 180 $^{o}\phi$ and required clamping over longer lengths to prevent significant reflections. Two operators in telephone communication easily made the remote adjustments. Bowing in of the narrow wall of the waveguide decreases its phase length, and bowing in of the broad wall (with consequent bowing out effects on the narrow wall) increases its phase length.

The measurement system is capable of reproducing measurements within ± 0.1 ($^{\circ}\phi$). The modulator flanges have a calibration accuracy of better than ± 0.3 ($^{\circ}\phi$). The networks have a phase stability of better than ± 0.5 ($^{\circ}\phi$). The accelerator sections are within ± 2.5 ($^{\circ}\phi$) of their design lengths. Thus, the overall accuracy of phase adjustment is better than ± 4.5 ($^{\circ}\phi$), allowing ± 1.0($^{\circ}\phi$) for temperature instabilities for the accelerator sections.

Figure 7 shows the distribution of phase-unbalance of the waveguide components before tuning. Measurements were made, at most klystron stations of the phase-unbalance from the klystron port to the input port of the lower power divider; and at all stations, of the S-assemblies (the quarter-power portions of the rectangular waveguide network, including the lower power divider). Separate data are shown for S-assemblies at odd- and even-numbered klystron stations because of the alternating feed arrangement shown in Fig. 1. The data show that the rectangular waveguide cross-over branch is correctly designed, as its location in the network does not affect the mean phase-unbalance. The $15^{\circ}\,\phi$ mean unbalance did not warrant adjustment of the design of the rectangular waveguide network during manufacture.

In conclusion, the modulated reflection scheme has been found to work very well on the large, single-input port, multi-output port, waveguide networks. The greatest errors come from limited control over the environmental parameters. The use of a diode for the modulated reflector is very satisfactory as long as the microwave power level at the diode was kept low (a few milliwatts). If this type of scheme is used at different frequencies, either to make absolute phase length measurements or to measure the phase versus frequency characteristics of a network, the reflector and the microwave comparison circuit must be broadbanded or calibrated as a function of frequency.

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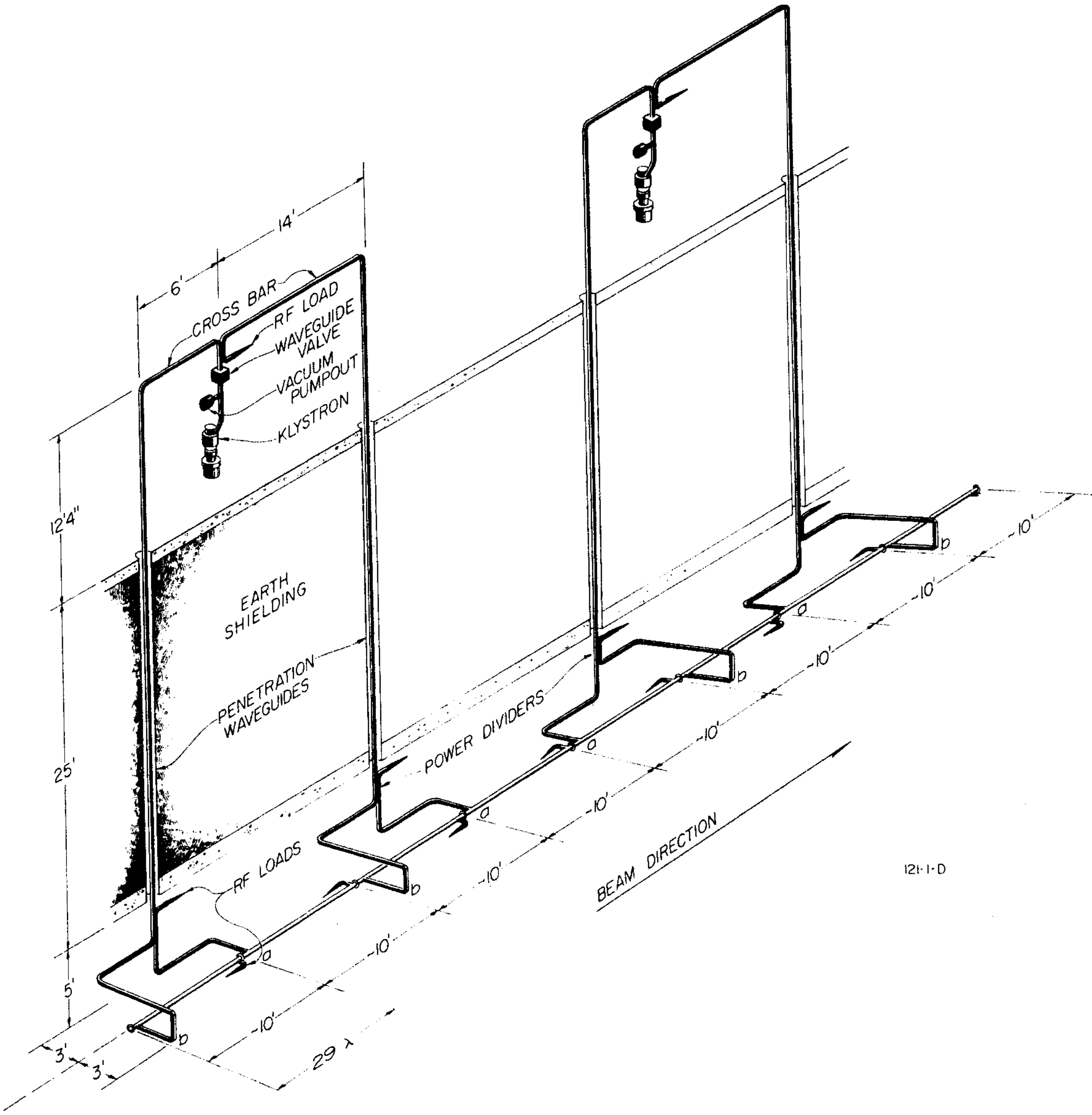

FIG. 1 -- WAVEGUIDE NETWORK

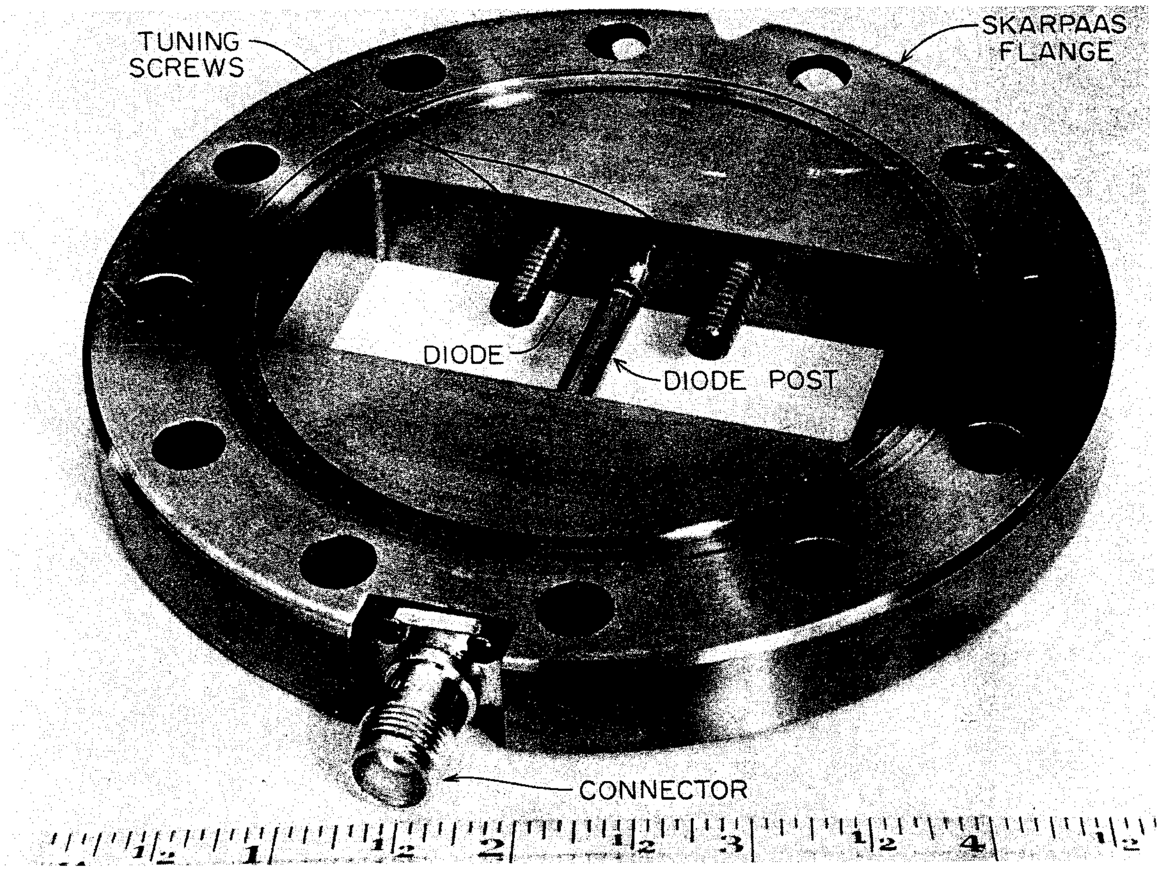

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FIG. 2 -- MODULATOR FLANGE

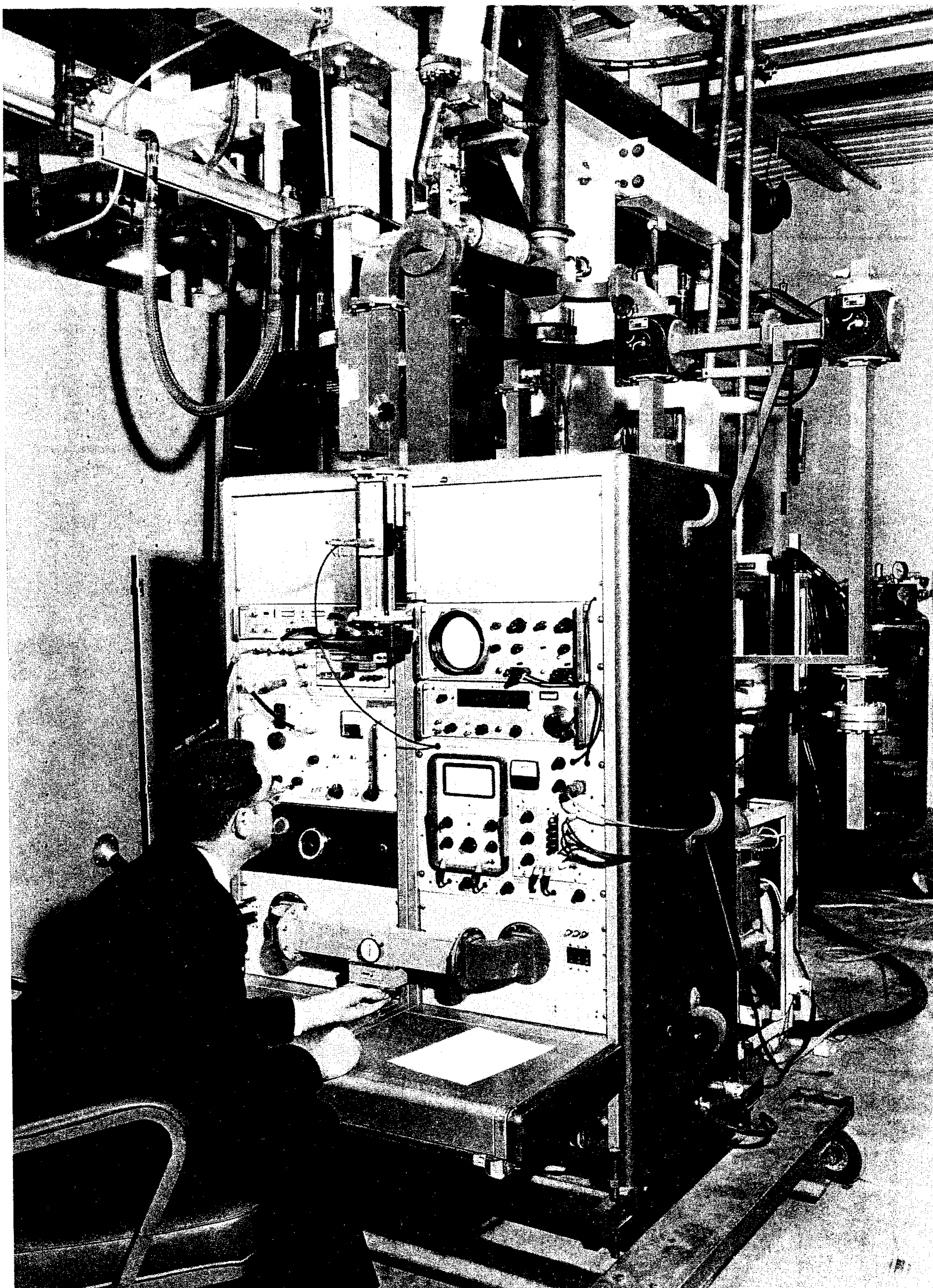


Fig. 3 - PHASING MACHINE CONSOLE

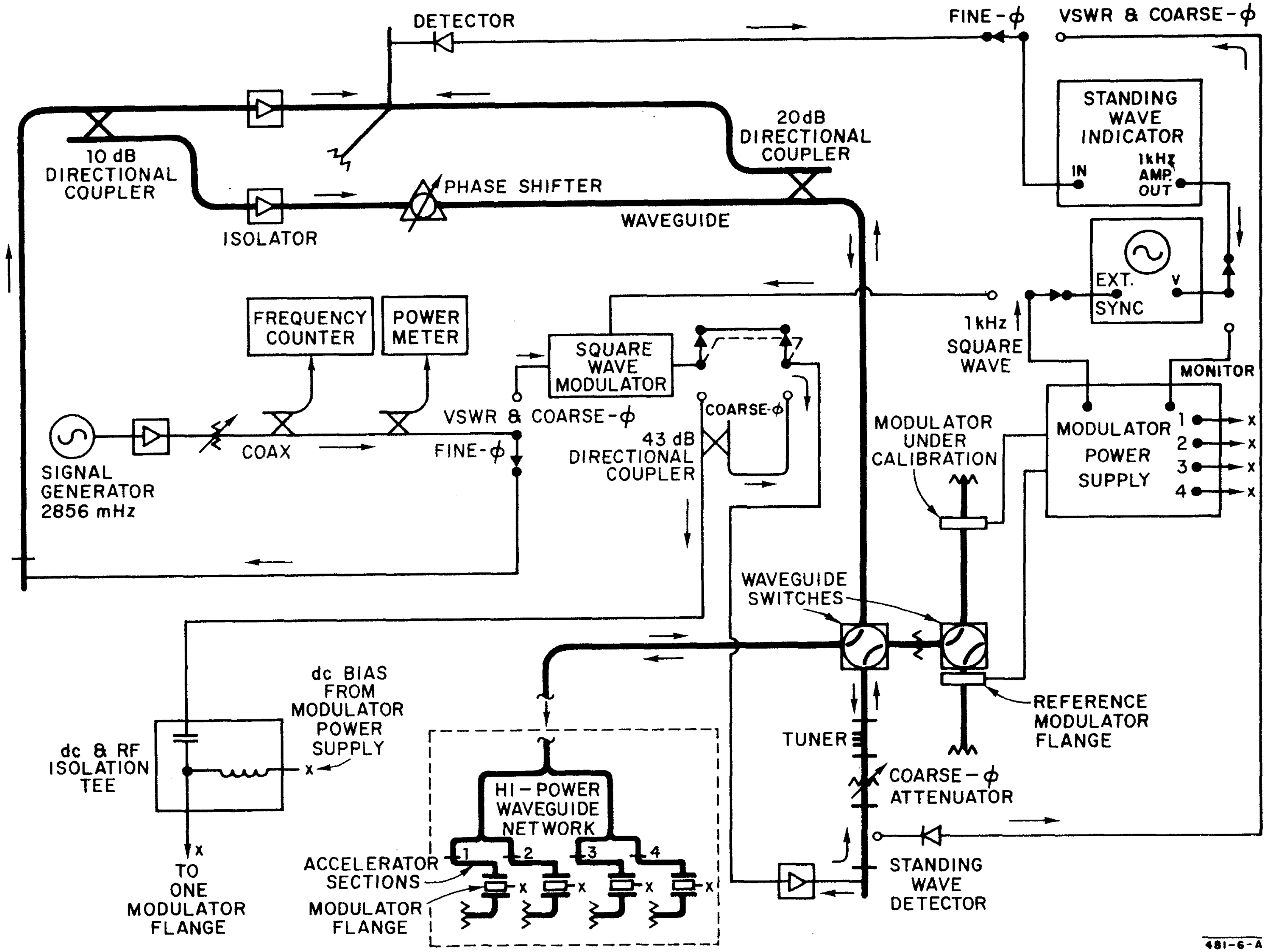
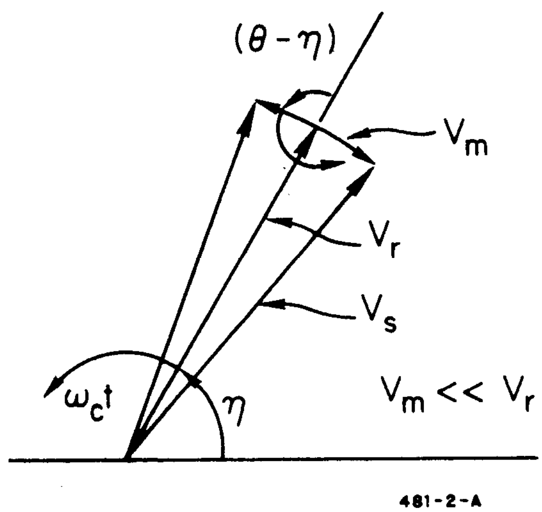


FIG. 4 -- BLOCK DIAGRAM OF PHASING MACHINE



$$v_r = V_r \cos\,(\omega_c t + \eta) \tag{1}$$

$$v_m = V_m \left[\left(\frac{2-m}{2}\right) + \frac{2m}{\pi} \sum_{n=o}^{\infty} \frac{\cos(2n+1)\,\omega_m t}{(2n+1)}\right] \cos(\omega_c t + \theta) \tag{2}$$

$$v_s = \left\{ \text{dc terms} + \frac{4mV_m}{\pi} \left[\left(\frac{2-m}{2}\right) V_m + V_r \cos(\theta - \eta)\right] \cos \omega_m t \right.$$
$$\left. + \text{ harmonic terms} \right\}^{1/2} \cos\left[\omega_c t + \alpha(\omega_m t, \eta, \theta)\right] \tag{3}$$

A null in the amplitude modulation of v_s at the frequency ω_m occurs for $\left(\frac{2-m}{2}\right) V_m + V_r \cos\,(\theta - \eta) = 0$ or

$$(\theta - \eta) = \cos^{-1}\left[\frac{-\,V_m\,(2-m)}{2V_r}\right] \approx \frac{\pi}{2} \quad \text{and} \quad \frac{3\pi}{2}\ , \tag{4}$$

where $0 < m < 1$ and $V_m \ll V_r$.

Fig. 5--Equations and vector diagram showing quadrature null conditions.

Phase Coefficient	$\theta_f \frac{(^\circ\phi)}{(kHz)}$	$\theta_T \frac{(^\circ\phi)}{(^\circ F)}$
70 feet Waveguide Network Branch	+ 0.037	+ 1.0
10 foot Accelerator Section	+ 0.30	+ 7.9

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Fig. 6--Phase length coefficients

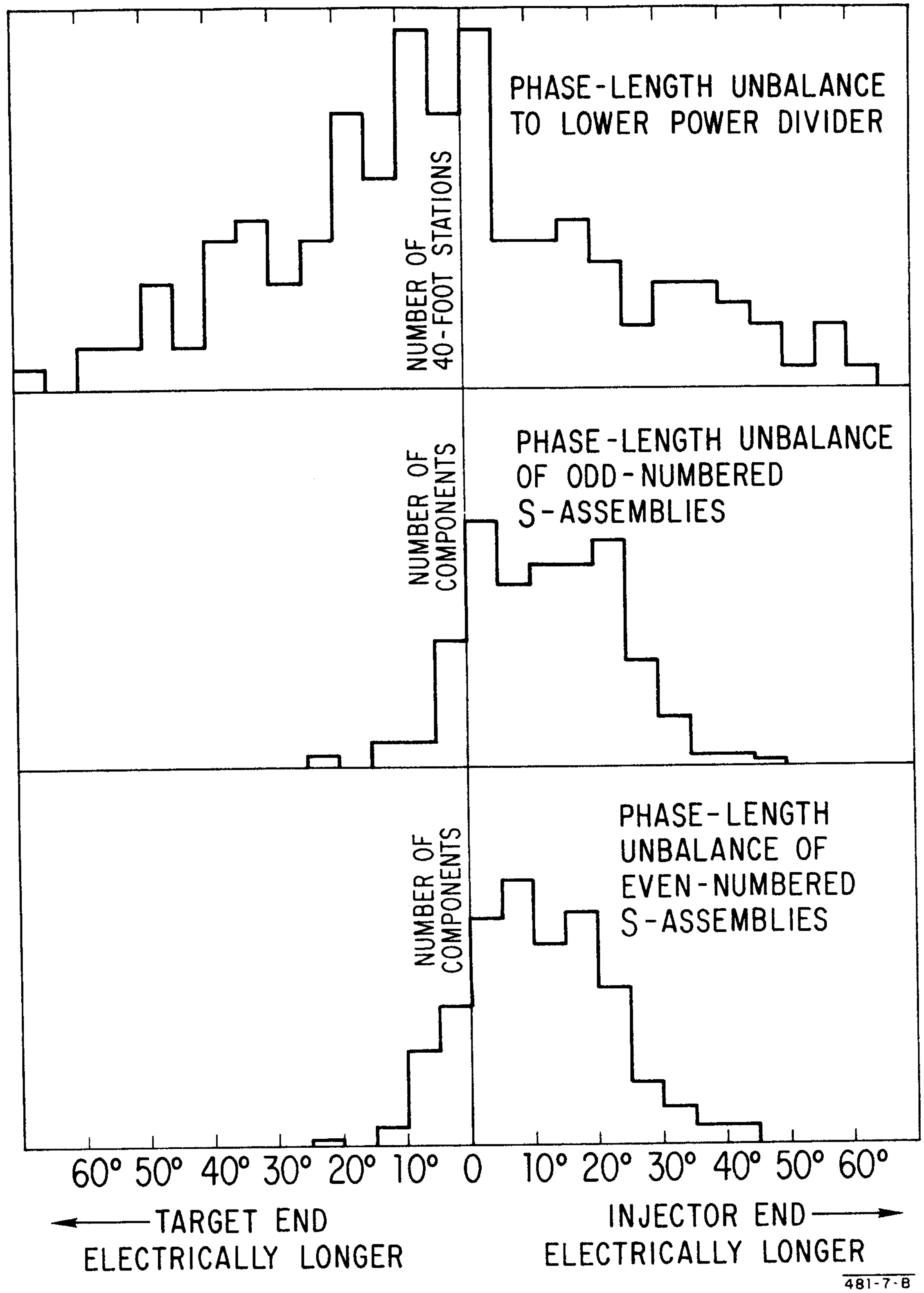

FIG. 7 - GRAPHS OF PHASE LENGTH ERRORS DUE TO MANUFACTURING TOLERANCES.