COMSAT GENERAL RANGING EQUIPMENT DEVELOPMENT*

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Summary. The range to the spacecraft is an important parameter for determining the transfer and synchronous orbits. The ranging equipment developed for the COMSAT General TT&C earth stations uses a fixed-tone technique to determine the distance from the earth station antenna to the satellites. Specifically, the range is calculated from the round trip propagation delay, which is determined by measuring the phase shift in four coherent audio tones.

This system is similar to the ranging equipment used at the INTELSAT earth stations. New integrated circuit (IC) technology has permitted individual tone transmission which was previously not available.

The ranging tones are frequency modulated in both the up- and down-links in the INTELSAT system. However, in the COMSAT General system the tones are frequency modulated in the up-link and phase modulated in the down-link. Hence, new techniques are required to determine the phase shift of the earth station equipment.

Introduction. The fixed-tone ranging system developed for the COMSAT General TT&C earth stations uses four coherent high-spectral-purity audio tones. The frequencies of these tones have been chosen to meet the following criteria:

a. the lowest frequency tone ($f_1 = \omega_1/2\pi$) satisfies the maximum range ambiguity requirement, i.e., $\tau_{max} = 2\pi/\omega_1 = 2d_{max}/c$, where c equals the velocity of light;

b. the phase ambiguity of higher frequency tones is resolved by the lower frequency tones; and

c. the highest frequency tone generates the desired accuracy. Four frequencies (35.4 Hz, 283.4 Hz, 3.968 kHz, and 27-778 kHz) were previously designated.**

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** The four frequencies are common to synchronous orbit satellites using fixed-tone ranging.

The accuracy of the range measurements in this system depends on the phase stability of the equipment at these four frequencies. To achieve accurate, stable phase readings it is essential to maintain a high degree of noise immunity for the tones by using narrowband filters in the detector. These filters inherently produce phase shifts which vary substantially as a function of frequency and temperature. It is therefore necessary to employ a very stable oscillator in the tone generation and to ovenize several of the filters in order to reduce the equipment's temperature sensitivity.

Two methods of tone transmission and detection are provided in this system. The first is the SUM mode of transmission, in which the selected tones are summed together. The alternate method is the FM mode, in which the lower frequency tones, as selected, are frequency modulated onto a 19-kHz subcarrier which is summed with the 27.778-kHz tone. One of these composite tone signals is then frequency modulated on a 70-MHz carrier in the up-link path and phase modulated on a 70-MHz carrier in the down-link.

Previously, in the INTELSAT system, the phase shift of the earth station equipment (commonly known as a zero range calibration) was measured by simply looping the tones back at RF using a transponder (or frequency translator) on the antenna. Because both the up-link and down-link signals were frequency modulated in the IF, no additional equipment was necessary. In the COMSAT General system, however, the change in IF modulation on the downlink caused a problem in determining the zero range calibration. This problem required the development of an FM-to-PM converter or range calibrator which would then be used to correctly interface the equipment for the zero range calibration.

This range calibrator is part of the TT&C equipment at the COMSAT General earth stations and will also be used in those INTELSAT TT&C stations providing launch support.

Range Processor Operation. The range processor unit is equipped with a manual front panel control and an interface to an HP2100 minicomputer to permit remote operation. Specifically, the processor unit under computer control generates the ranging tones, combines them for transmission, detects the received tones, provides the reference and processed signals to the phase meter, and transfers the phase shift measurements to the computer.

Two modes of transmitting the ranging tone are provided: an FM mode and a SUM mode. The mode is selected by a manual front panel switch. A flag bit notifies the computer of the mode which has been selected.

In the FM mode, upon selection, the three lower frequency tones, 35.4 Hz, 283.4 Hz, and 3.968 kHz, are frequency modulated on a 19-kHz subcarrier which is then summed with the 27.78-kHz tone. This combined signal frequency modulates the 70-MHz carrier, providing 400-kHz peak deviation. Simultaneous or sequential tone transmission is possible, with the levels automatically preset to provide approximately 400-kHz peak deviation of the 70-MHz carrier.

In the SUM mode the three higher frequency tones, 283.4 Hz, 3.968 kHz, and 27.78 kHz, are summed and the combined signal directly modulates the 70-MHz carrier. The 35.4-Hz signal is transmitted by SSB amplitude modulating the 3.968-kHz tone. Actually the amplitude modulation is synthesized by developing the sideband frequency from a divider chain. When all four tones are transmitted simultaneously, a severe problem exists in maintaining the range processor calibration. This is due to the sharp filter which would be required in the range processor receiver to separate the 3.968-kHz tone from the 4.003-kHz sideband. This problem has been avoided by restricting the transmission of the 35.4-Hz information to those intervals when it is measured.

A divider chain shown in Figure 1 is used to produce five square waves from a master oscillator of 6.2778 MHz with a stability of 3 x 10^{-6}. To implement the divider chain, synchronous parallel load binary and decade counters are used. To generate the 27.78-kHz tone the master oscillator is divided by 226, which is factored into 113 x 2. The divide by 13 is accomplished by loading an initial number and allowing the counter to reach its maximum value of 2^N - 1.

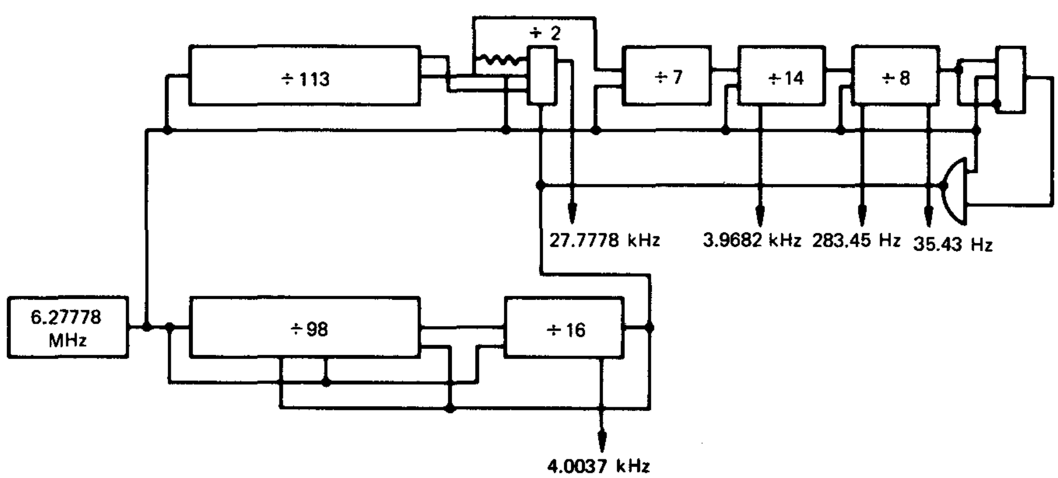

Figure 1. Ranging Transmitter Divider Chain

Since the counters are synchronous the reset decode must occur one count before the desired reset. The reset loads the predetermined start number via the parallel load input. The start number is given by 2^N - 1 - (m - 1), where N is number of bits in the counter and m is the frequency division required. In the case of divide by 113, the start number is 143.

This number is hard wired to the parallel load inputs by connecting the 2^0, 2^1, 2^2, 2^3, and 2^7 inputs to a logic “1” and the 2^4, 2^5, and 2^6 inputs to a logic “0”. The reset decode state is all “1’s” and is detected internally in the counters so that no additional external logic is required. The final divide by 2 is separated from the counter to ensure that a square wave output is presented to the narrowband ovenized crystal filter which produces the required sine wave.

The remaining square waves, 4.003 kHz, 3.968 kHz, 283.4 Hz, and 35.4 Hz, are produced in the same manner and are passed through a bandpass-low-pass filter combination in which the low-pass filter rejects the higher frequency components and the bandpass filter in combination with the low-pass filter rejects the third harmonic component. The Q’s of the filters are selected to minimize the phase change as a function of temperature and to provide sufficient rejection of the harmonic components.

The sine wave outputs from the filter unit are routed to three units in parallel: the reference select unit, the FM transmit unit, and the SUM transmit unit (see Figure 2). The inputs to the latter two units are routed via relays which are operated by the control logic. The same control logic applied to a programmable operational amplifier unit selects the appropriate amplifier for which the gain has been preset to properly adjust the output voltage; thus, the change in the 70-MHz deviation is minimized. From the computer or manually from the front panel, the control logic receives a 4-bit input, one bit per tone, which specifies the tone or tones which are transmitted. This signal is independent of the FM or SUM mode. Both modes are operated continuously, with the output selected by the front panel switch. Two additional bits are used to control the reference select unit, which routes the desired tone to the reference input of the phase meter. This unit is also a programmable operational amplifier but with equal gains. The control logic unit prevents transmission of the 35.4-Hz tone unless a 35-Hz measurement has been requested.

In the receiver section (see Figure 3) the signal is immediately separated into two paths. One path is through a gain select unit, which is controlled by the same four bits described above for the control logic. This signal is passed through a 27.78-kHz ovenized bandpass crystal filter, amplified, and connected to the output tone select unit, which is controlled by the same two bits used to select the phase meter reference input signal. The second path is through an amplifier and a 27.78-kHz band reject filter to strip out the 27.78-kHz tone. This signal then splits again, with one path for the FM mode and one for the SUM mode. In the FM mode it enters a discriminator to recover the lower frequency transmitted tones, which are then appropriately amplified in another programmable operational amplifier unit and routed to the bandpass filters. The SUM mode path bypasses the filter and is routed directly to the selectable gain amplifiers and then to the bandpass filters to improve the signal-to-noise ratios.

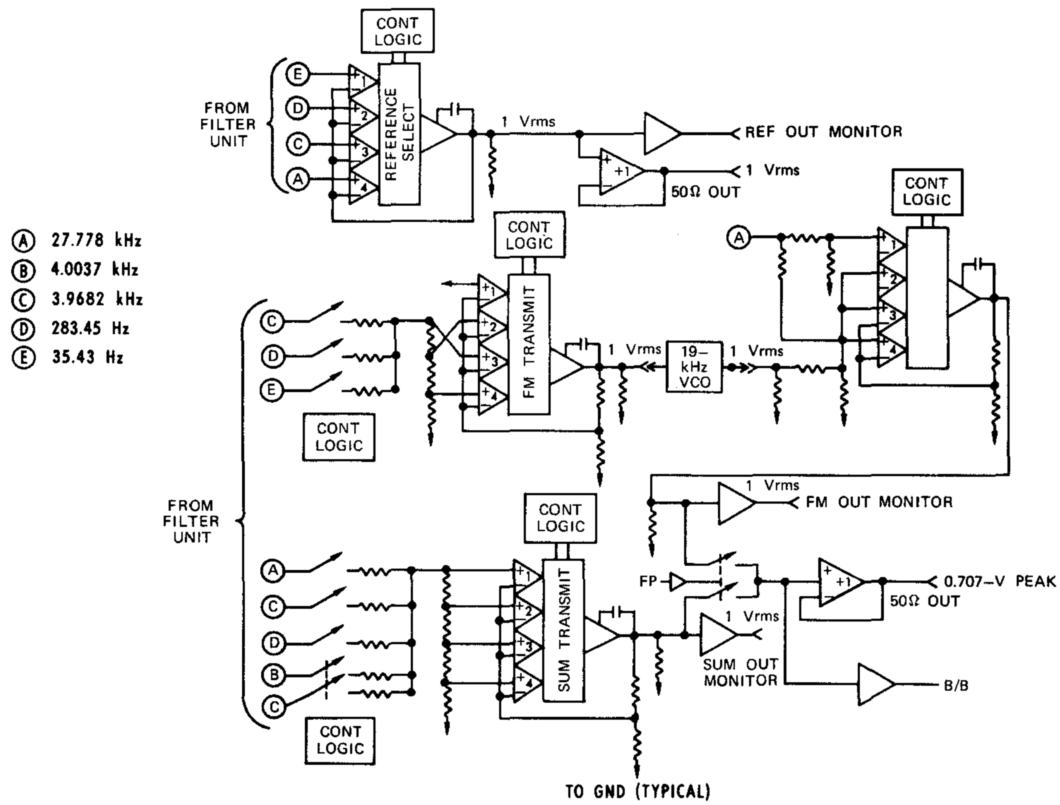

Figure 2. Ranging Transmitter Transmit Control

One of these two paths will always be turned off by the front panel mode switch. This switch will also select the 35.4-Hz signal path to its bandpass filter. In the SUM mode the 35.4-Hz tone will be recovered by square law detection and passed through a low-pass filter. The signal is then bandpass filtered by the same filter used for the FM mode. The bandpass filter outputs are routed to the output select unit described above.

Present technology has greatly enhanced the ranging processor design by providing increased accuracy, greater flexibility, and remote control.

Ranging and Range Calibration. In the INTELSAT system, ranging to the satellites is accomplished by passing the signal through the communications transponders. The up- and down-link signals are both 70-MHz FM at IF, and normal ranging presents no problems. Zero range calibration is done by simply looping the signal back at the earth station using a transponder on the antenna. The only drawback to this type of system is that a portion of the satellite’s communications capacity is used for ranging.

In the COMSAT General system this reduction in capacity has been avoided by using the command receiver and beacon generator for ranging. Thus the signal which is received as a 70-MHz frequency modulated signal is transmitted back to the earth as a 70-MHz phase modulated signal. This presents no problems in terms of commands or telemetry data,

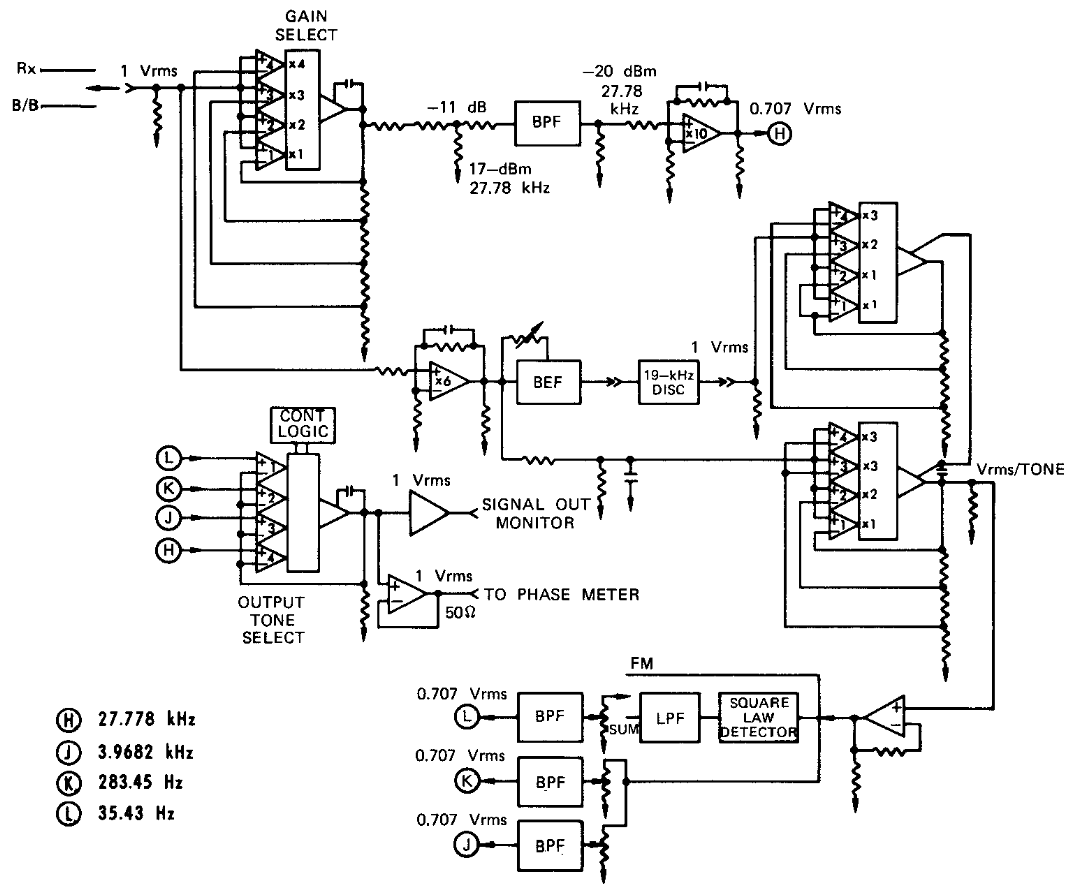

Figure 3. Ranging Receiver

since these functions are never performed concurrently with ranging. However, as mentioned previously, calibrating the phase shift of the earth station equipment does present a problem. Figures 4a through 4c are block diagrams of the proposed IF and RF zero range calibration and ranging equipment configurations. The problem results from the use of the range calibrator for zero range calibration, but not for normal ranging.

The phase shift measured in ranging (Figure 4c) is as follows:

$$\phi_{MEAS} = \phi_{RANGING\ PROCESSOR} + \phi_{FM\ MODULATOR} + \phi_{U/C} + \phi_{SATELLITE} + \phi_{D/C} + \phi_{PM\ RCVR} + \phi_{CABLES} + \phi_{RANGE} \quad (1)$$

The phase shifts due to the up-converter ($\phi_{U/C}$) and down-converter ($\phi_{D/C}$) may be eliminated from equation (1) since they are insignificantly small. Then

$$\phi_{MEAS} = \phi_{RANGING\ PROCESSOR} + \phi_{FM\ MODULATOR} + \phi_{SATELLITE} + \phi_{PM\ RCVR} + \phi_{CABLES} + \phi_{RANGE} \quad (2)$$

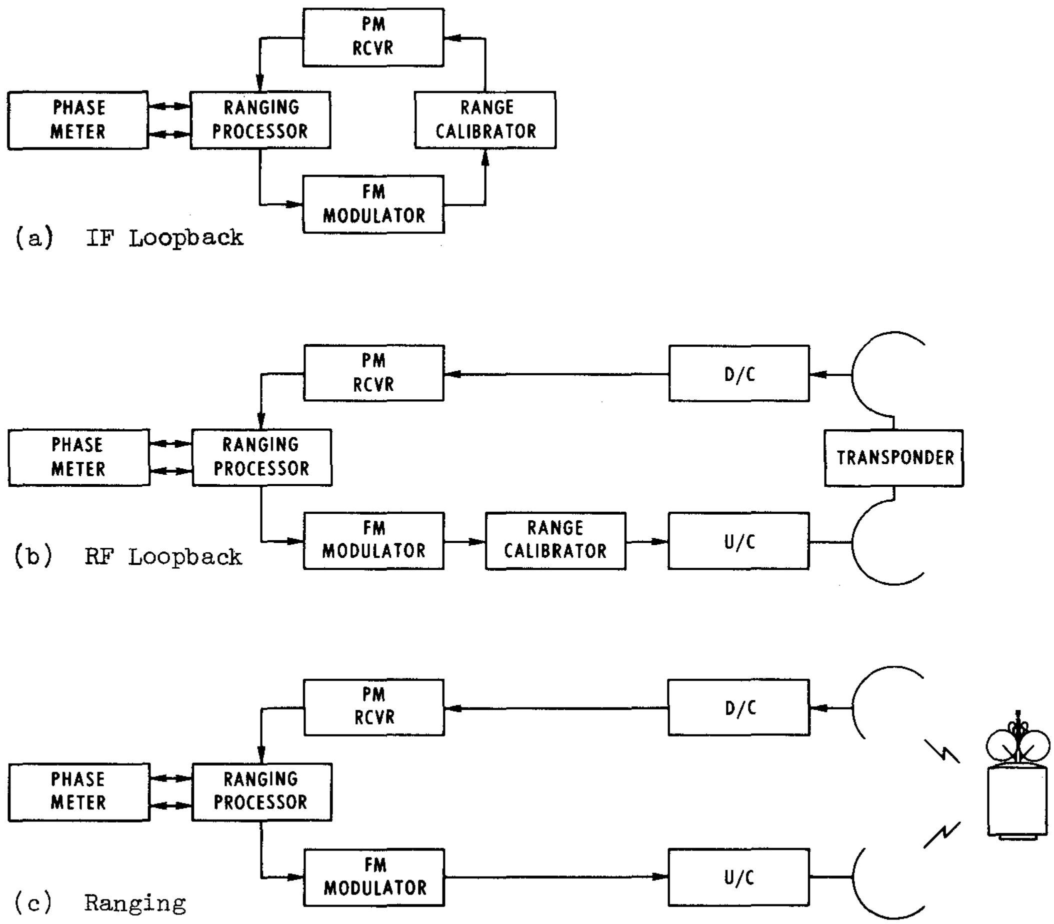

Figure 4. Typical Equipment Configurations for Zero Range Calibration (both IF and RF) and Ranging

It can be seen that, to remove the phase shift due to the range (ϕ_{RANGE}) from the measured phase shift, the phase shifts due to the ranging processor ($\phi_{RANGING\ PROCESSOR}$), the FM modulator ($\phi_{FM\ MODULATOR}$), the spacecraft equipment ($\phi_{SATELLITE}$), the PM receiver ($\phi_{PM\ RCVR}$) and the cables (ϕ_{CABLES}) must be determined.

In an RF zero range calibration (Figure 4b) the following is measured:

$$\begin{aligned}\phi_{RF\ CAL} = \ & \phi_{RANGING\ PROCESSOR} + \phi_{FM\ MODULATOR} \\ & + \phi_{RANGE\ CALIBRATOR} + \phi_{U/C} \\ & + \phi_{TRANSPONDER} + \phi_{D/C} + \phi_{PM\ RCVR} + \phi_{CABLES}\end{aligned} \quad (3)$$

The phase shifts due to the up- and down-converters and the transponder may be eliminated since they are approximately zero, yielding

$$\begin{aligned}\phi_{RF\ CAL} = \ & \phi_{RANGING\ PROCESSOR} + \phi_{FM\ MODULATOR} \\ & + \phi_{RANGE\ CALIBRATOR} \\ & + \phi_{PM\ RCVR} + \phi_{CABLES}\end{aligned} \quad (4)$$

Comparison of equations (2) and (4) indicates that an RF zero range calibration can be used to eliminate all the unwanted phase shifts in the ranging measurement, except for the phase shift of the satellite, at the expense of adding the phase shift due to the calibrator. Similarly, the IF zero range calibration (Figure 4a) measurement yields

$$\begin{aligned}\phi_{\text{IF CAL}} = \; & \phi_{\text{RANGING PROCESSOR}} + \phi_{\text{FM MODULATOR}} \\ & + \phi_{\text{RANGE CALIBRATOR}} \\ & + \phi_{\text{PM RCVR}} \end{aligned} \tag{5}$$

which contains the same unwanted quantities with the exception of the phase shift due to the cables, which can be determined by other simple measurements.

The phase shifts of the calibrator and the satellite are the only remaining unknown parameters and they cannot be determined absolutely.*** However, they can be generated from several indirect measurements. Figure 5 is a block diagram of the range calibrator. The FM discriminator, amplifier, and PM modulator are all wideband units which will generate very nearly zero or 180° phase shift.**** The absolute phase shift of the amplifier can be measured since its input and output are both baseband signals. The phase shift of the PM modulator can also be measured absolutely using two phase locked modulators and a mixer (see Figure 6). The phase shift of the discriminator with an FM modulator (also wideband) can be measured as a pair and has been found to be 180° ± 2° over the frequency range of interest. If half of the difference from 180° is assigned to each unit, the maximum possible error incurred is 1° at any frequency. These readings may be incorrect by a multiple of 360°, but this is also true of any of the other readings and can be shown to be inconsequential.

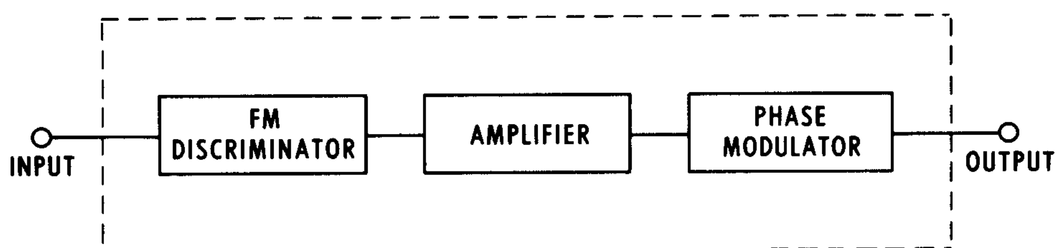

Figure 5. Block Diagram of Range Calibrator

*** This is due to the difference in nature between the input and output signals.

**** Depending upon the modulation or detection technique, and the type of amplifier, inverting or noninverting.

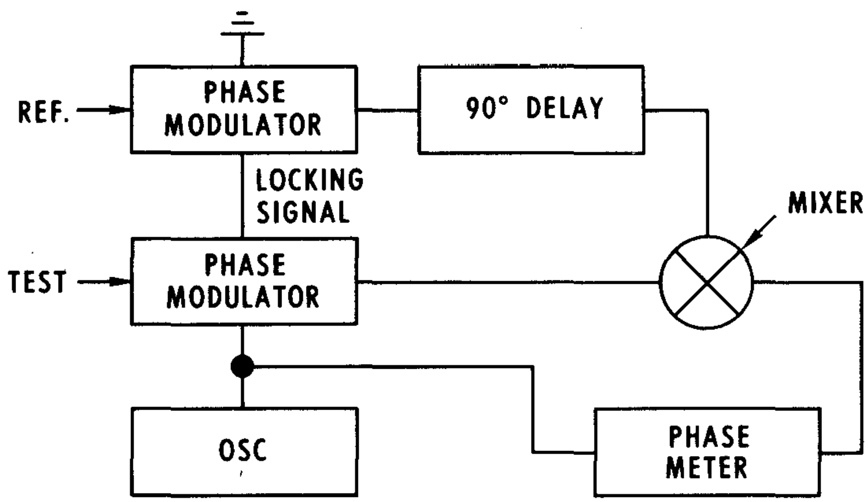

Figure 6. Test Configuration for Measuring Phase Shift in Phase Modulator

The phase shift of the calibrator has now been generated and can be used to determine the phase shift of the spacecraft ($\phi_{SATELLITE}$). In Figures 4a and 4c, if an IF loopback is measured and then a ranging measurement to the spacecraft is made in an anechoic chamber, the difference between these readings will generate the phase shift of the spacecraft relative to that of the calibrator. Since the phase shift of the calibrator is known, that of the spacecraft is now deduced and the phase shift due to the range (ϕ_{RANGE}) in equation (2) can be determined.

Conclusions. The ranging system implementation discussed in this paper is tailored to the command and telemetry link characteristics of the COMSAT General COMSTAR and MARISAT satellites. The system has been engineered to provide the ranging performance and flexibility needed for these satellites. A problem of particular interest that has been solved relates to the use of frequency modulation on the up-link and phase modulation on the down-link and the needed calibration procedure.

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