NATIONAL RADIO ASTRONOMY OBSERVATORY

Electronics Division Internal Report No. 56

# A POSSIBLE LOCAL OSCILLATOR DISTRIBUTION SYSTEM FOR THE NRAO INTERFEROMETER AND ANALYSIS OF ITS PHASE INSTABILITIES

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JUNE 1966

NUMBER OF COPIES: 75

# A POSSIBLE LOCAL OSCILLATOR DISTRIBUTION SYSTEM FOR THE NRAO INTERFEROMETER AND ANALYSIS OF ITS PHASE INSTABILITIES

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Summary

This report describes a LO signal distribution system using frequency multipliers. It gives graphs for deriving the optimum transmission frequency from a point of view of loss. Also, a quantitative analysis of the expected sources of phase instabilities in such a distribution system is given. Finally, a number of recommendations is presented on how to make a distribution system with as good as possible an intrinsic stability. These recommendations apply to any cable distribution system.

## Specification

A LO signal at a frequency of about 2700 MHz has to be provided to the mixers in the front end boxes of each of the two elements of the interferometer. The relative phase of the sine waves supplied to the mixers has to be known at any instant. Two types of instabilities can be distinguished.

a. Short term phase variations — variations which are fast with respect to the duration of the measurement of one Fourier component — around a mean value.

b. Long term variations of the aforesaid mean.

The duration of one measurement is 60 seconds. If the values of the phase variations have a symmetrical distribution around their mean value during this period, they are relatively harmless. For example, if the distribution is rectangular in shape with a maximum deviation of ± 15° phase, the only result is an integrated fringe amplitude decrease of 1%. Variations of ± 20° cause 2% decrease; ± 30° cause 5%.

Long term phase variations, if known, can be corrected for in the computation. Calibration of the overall receiver system phase can be done on some radio sources. A reasonable period between two such calibrations is 24 hours. In the meantime the system phase preferably has to be stable or must be monitored.

## Description of Distribution System

A sketch of the interferometer baseline is given in fig. 1. In this diagram the positions or stations where an interferometer element can be located are marked with a cross. The position of the not movable element is marked with a circle. The LO signal must be provided to each of these positions. A stable LO signal generator will be housed in the central control building, marked CCB; the CCB is offset from the baseline by 100 m. For the LO signal transmission medium is chosen a Prodelin Spiroline 50 ohm, 1 5/8" diameter coaxial cable. The cable runs along the baseline, with tap off points at the different stations. Coaxial cable is mechanically simple, shows good stability, requires no maintenance and is relatively cheap for the considered length of the baseline. The rather high loss of 54 dB/km at 2.7 GHz can be partly overcome by transmitting a lower frequency signal over the cable followed by frequency multiplication at each element. The maximum distance over which the LO signal is to be transmitted is 1700 m. This figure includes 100 m of cable from the distribution cable at ground level to the focus of the 85-ft. reflectors. The maximum path length difference of the cables from the LO master oscillator in the CCB to the interferometer elements is 1200 m. This occurs when observations with 1800 m spacing (station 18) take place. (See Table 1. p. 11.)

## Optimum Frequency of Transmission for LO Signal

As stated before, because of the rather high cable loss at frequencies around 2.7 GHz, we would welcome a system of lower frequency transmission and frequency multiplication, if losses in multipliers are not prohibitive. A figure for frequency multiplier loss, which appears to be well within the capability of present day multipliers, is 10 dB per decade. In order to find an optimum frequency of transmission from the point of view of loss, sets of curves are drawn in figures 2a and 2b. These diagrams give loss versus frequency for various lengths of 1 5/8" and 7/8" diameter cable, respectively, together with frequency multiplier loss. The sum curve of cable loss plus multiplier loss is also given. The sum curves show broad minima. The frequency for which minimum loss is obtained depends on cable length. See figure 3.

For 900 m, 1 5/8" cable, which is the average length of the cable runs, the optimum frequency is about 195 MHz. This suggests a X14 multiplier.

This X14 multiplication factor can be obtained from a one stage step recovery diode or snap off varactor multiplier, with good efficiency.

In general, too high multiplication factors are undesirable because:

1. It leads to multistage multipliers, and
2. This limits the number of ways in which cable phase lock or monitor can be performed.

In multistage multipliers, the phase errors that occur in the first stage are multiplied up in subsequent stages, giving a worse overall phase stability.

As a general rule of practice, phase measuring setups of the same principle but operating at different frequencies obtain the same accuracy. If the frequency multiplier is not included in the phase measurement, then the higher the multiplication factor the worse the resulting overall phase error if the same output frequency is to be obtained.

## The SLAC Frequency Multiplier and a Possible Distribution System

For the new two mile Stanford Linear Accelerator a reference frequency of 2860 MHz is distributed along the full two mile long system. The required phase accuracy is ± 5°. In this case distribution at 476 MHz over a 3 1/8" coaxial cable is followed by X6 frequency multiplication. The multiplier has the very good phase stability of ± 1° at the output frequency over a wide range of environmental conditions. For 3 W input power it delivers more than 400 mW at the output. With a slight modification, as regards the output frequency, this multiplier is directly applicable in the distribution system of the NRAO interferometer.

Although a X6 frequency multiplier is not optimal from the point of view of loss, it is only slightly off, as a glance at the curves of fig. 2a shows.

A possible distribution system using this multiplier is shown in figure 4. The high output power is mainly necessary for pumping the degenerate paramp, the balanced mixer requiring not more than 2 mW. A cable phase length monitoring system using Swarup and Yang's principle is incorporated.

## Instabilities

The calculation of phase instabilities, as presented in the following, is independent of the choice of the transmission frequency, but depends only on the final frequency that is used as the LO signal, in our case about 2700 MHz.

The phase of the 2700 MHz signal can change in three variables $\Delta\omega_{LO}$, $\Delta\tau$ and $\Delta\varphi$:

$$(\varphi_{LO} + \Delta\varphi_{LO}) = (\omega_{LO} + \Delta\omega_{LO})(\tau + \Delta\tau) + (\varphi + \Delta\varphi)$$

$$\Delta\varphi_{LO} \cong \Delta\omega_{LO}\tau + \omega_{LO}\Delta\tau + \Delta\varphi$$

$\varphi_{LO}$ — phase of LO signal at element mixer input.

$\omega_{LO}$ — LO frequency in radians per second.

$\tau$ — propagation time from LO signal generator in CCB to element.

$\varphi$ — phase shift in amplifiers, etc.

$\Delta$ — denotes a change.

### 1. Variations in LO Frequency $\Delta\omega_{LO}$

If the delay $\tau$ from the central oscillator to the different elements of the interferometer is equal, no variation in relative phase with frequency will occur. In the case of the NRAO interferometer the maximum cable length difference is 1200 m. This corresponds to a delay difference $\tau$ of

$$\tau_{diff} = \frac{1200}{300 \times 0.85}\ \mu s \cong 5\ \mu s$$

A maximum "short term" phase error of $\pm$ 15° requires a LO frequency stability of

$$\Delta\omega_{LO} = \frac{\Delta\varphi_{LO}}{\tau} = \frac{\frac{15\ \pi}{180}}{5 \times 10^{-6}} \cong 4 \times 10^{4}\ \text{rad/s}$$

equation continued --

$$\Delta f_{LO} = \frac{\Delta\omega_{LO}}{2\pi} \cong 6000 \text{ Hz}$$

This corresponds to a relative stability of about $2.5 \times 10^{-6}$. Long term frequency stabilities of the order of $5 \times 10^{-8}$ are required to make this cause of phase error negligible.

## 2. Variations in Propagation Time $\Delta\tau$

Variations in propagation time have two causes:

a. Variations with cable temperature.

b. Variations with cable internal pressure.

The temperature coefficient of coaxial cable is only very seldom known or specified by cable manufacturers. If the construction of a cable is known in sufficient detail the temperature coefficient can be calculated using the W. C. Erickson— A. Watkinson method (BCAP - Memo 24A, Dec. 21, 1962). This was tried for the 1 5/8" and the 7/8" Prodelin Spiroline 50 ohm coaxial cable with the following results:

| | |
|---|---|
| 1 5/8", free-to-move | $-25 \times 10^{-6}/°C$ |
| 7/8" , free-to-move | $-24 \times 10^{-6}/°C$ |
| 1 5/8", fixed-in-position | $-45 \times 10^{-6}/°C$ |
| 7/8" , fixed-in-position | $-45 \times 10^{-6}/°C$ |

As there are a few reasons for inaccuracies in these calculated figures (see the report mentioned above), the only way to be sure is to perform measurements. This was done by the Stanford Linear Accelerator Group. The figures found there were:

| | | |
|---|---|---|
| 1 5/8" | -43 ps/°C/km | or $-13 \times 10^{-6}/°C$ |
| 7/8" | -16 ps/°C/km | or $-5 \times 10^{-6}/°C$ |
| 1/2" | $\pm$16 ps/°C/km | or $-5 \times 10^{-6}/°C$ |

The 1 5/8" figure was confirmed by S. Zisk (Stanford RA Center). The difference in behavior between 1 5/8" and the other size cables is as yet unexplained. All three cables are of the same construction and are scaled versions of each other. For the following calculations we will assume a temperature coefficient of -40 ps/°C/km.

The cable system can be divided into two parts that need separate treatment. The buried cable is at a rather stable temperature but the path length difference of the runs between the interferometer elements can become as big as 1200 m. The exposed cables leading from the buried distribution cable to the focus are of equal length but are subjected to large environmental temperature changes. However, only differential temperature between the two elements is important.

The buried cable. Supposing that the soil is homogeneous over the length of the baseline, the buried cable will be at the same temperature everywhere and will be subjected to the same temperature variations. If the cables leading to the elements were of equal length, any phase variation due to temperature change would cancel out. For the NRAO interferometer a maximum difference of 1200 m must be taken into account. For this length of cable the absolute temperature changes are important. These temperature changes were measured by Venugopal and are not bigger than 0.05 °C per 24 hours at a depth of about 1 m, despite variations in surface temperature of as much as 20 °C.

The observed temperature variations give rise to a peak to peak delay variation during 24 hours of

$$40 \times 10^{-12} \times 0.05 \times 1.2 = 2.4 \text{ ps p-p}$$

As soon as the interferometer becomes more symmetrical (i.e., movable elements at other stations), this delay change will decrease. The path length differences for the various baselines are given in Table 1.

The exposed cable. The length of the exposed cable will be 80 m maximum and we shall suppose it to be of equal length for all elements. We shall also assume it shielded from direct sunlight.

Air temperature variations at ground level and 10 m above the ground have been measured by G. Grove. The measurements show a maximum difference of 3 °C at ground level during one hour periods around dawn and dusk, and of 1 °C at 10 m above the ground. These are the biggest temperature variations recorded in a 7-week period, and they occur infrequently. For the calculation we will assume an average worst case temperature difference of 2 °C from ground level to focus. The resulting delay error will be

$$40 \times 10^{-12} \times 2 \times 0.08 \cong \pm\ 6.5 \text{ ps}$$

The temperature difference during most part of the day and night will be a factor two or three smaller. Using phase stable cable at this place, having a typical temperature coefficient of 4-8 ps/°C/km, would reduce the delay error figures to negligible values. Using normal cable an improvement can be obtained by temperature isolation.

Variations with internal gas pressure are balanced out if cable runs to the different elements are of equal length. In the case of the NRAO interferometer, a maximum length difference of 1200 m occurs. Gas pressure regulators with an accuracy of 0.01 psi (or 0.0007 atm) can be obtained. Assuming an accuracy of 0.001 atm, together with the figures obtained in memo IG 017 66, we find a delay error of

$$650 \times 10^{-12} \times 10^{-3} \times 1.2 \text{ s} \cong \pm\ 0.8 \text{ ps}$$

Adding all the delay errors we arrive at a total worst case delay variation over 24 hours of $\underline{\pm\ 8.5 \text{ ps}}$ and of $\underline{\pm\ 4 \text{ ps}}$ during most of the time except around dawn and dusk. Using temperature compensated cable for the exposed parts will essentially remove variations in this part of the system. A more symmetrical interferometer, as regards the position of the LO signal generator relative to the interferometer elements will further reduce the stated delay changes.

The phase errors as a result of the above given total delay changes are, respectively,

$$\pm\ 8.5 \times 10^{-12} \times 2.7 \times 10^{9} \times 360 \cong 8.5°$$

and

$$\pm\ 4 \times 10^{-12} \times 2.7 \times 10^{9} \times 360 \cong \pm\ 4°$$

## 3. Phase Variations $\Delta\varphi$

Phase errors occur because of a number of reasons:

a. Flexing of cables.

b. Variations in VSWR.

c. Variations or drifts in amplifiers and frequency multipliers.

Bending of only 1 m of flexible cable can easily cause phase variations of ± 20°, as measured in Leiden. It is clear from this figure that flexible cable has to be avoided. There are two possibilities to avoid normal flexible cable. One may use rotary joints or special flexible cable, designed for phase stability. No data are as yet available about the special flexible cable. Measurements performed on rotary joints by John Bringe at NRAO and in the BCAP group in Leiden indicate phase variations of these devices of less than 0.1° over 360° of rotation.

A change in VSWR of 0.03 gives a worst case phase error of 1°. In an inherently stable, low VSWR distribution system, it is believed that phase errors due to this cause stay smaller than ± 0.5°.

With adequate input power level and temperature stabilization day to day variations of less than ± 1° phase are easily obtained in amplifiers and multipliers.

## Conclusions

1. A transmission frequency of 450 MHz appears to be a reasonable compromise between phase error multiplication in frequency multipliers and the overall system loss. Experience in the Stanford Linear Accelerator group with a similar system using X6 multipliers is favorable.

2. A feed system, featuring equal transmission path lengths from the LO signal generator to the different interferometer elements, eliminates phase errors due to cable internal pressure, ground temperature variations and frequency offsets.

A phase-temperature compensated cable for the exposed parts of the cable system (about 80 m for each radio telescope) keeps phase changes caused by differential air temperature variations at a low level.

3. If an equal path length feed system is not desirable or possible for other reasons, the following is recommended to obtain good stability:

a. Use a crystal controlled LO signal generator with a sufficient long term (24 hour) stability; in our case $5 \times 10^{-8}$.

b. Bury the distribution cable at least 1 meter deep in the ground.

c. Make the exposed parts of the cable of exactly equal length. Shield them from direct sunlight. Put the cable as good as possible in identical positions on all the interferometer telescopes. If available, use compensated cable. If not, isolate the cable.

d. Rigorously stabilize internal gas pressure. A stability of 0.001 atm will reduce phase changes caused by pressure variations to almost negligible values.

e. Use rotary joints or possibly special designed flexible cable where necessary.

f. Pay attention to obtaining a low VSWR distribution system.

g. Stabilize temperatures and input power levels of amplifiers, multipliers and components containing ferrites or semiconductors.

4. The total predicted worst case phase error can be made less than $\pm 6°$ over most parts of the day. Only during about one hour periods near dawn and dusk a $\pm 10°$ phase error may occur. Table 2 gives a summary of the predicted phase errors.

5. Present interferometer phase errors prove to be bigger than those predicted. Possible reasons for this may be found in the following list:

Unequal lengths of exposed cable.

Insufficient pressure stabilization.

Use of flexible cable.

Unknown VSWR.

Other possible causes are:

Instabilities in paramps because of insufficient pump power stabilization and temperature stabilization.

Unknown behavior of atmosphere.

At present it is impossible to sort out the different causes of instability, although a correlation between water vapor content in the atmosphere and interferometer phase instabilities is found.

Acknowledgement

Ideas and/or data from the following people, whose names are not mentioned in the text, were used in the preparation of this report:

J. W. M. Baars (NRAO)

D. Farkas (SLAC)

R. McConnell (SLAC)

L. H. Sondaar (BCAP)

TABLE 1

TABLE OF ACTUAL PATH LENGTH DIFFERENCES FOR THE OBSERVED INTERFEROMETER SPACINGS

(Length is given in units of 100 m.)

| Interferometer Spacing | Path Length to Each Element | Path Length Inequality |
|---|---|---|
| 1 | 5, 6 | 1 |
| 2 | 6, 8 | 2 |
| 3 | 5, 8 | 3 |
| 4 | 2, 6 | 4 |
| 5 | 6, 11 | 5 |
| 6 | 5, 5 | 0 (6) |
| 7 | 5, 6 | 1 |
| 8 | 6, 14 | 8 |
| 9 | 5, 8 | 3 (9) |
| 10 | Not measurable | |
| 11 | Not measurable | |
| 12 | 5, 11 | 6 (12) |
| 13 | Not measurable | |
| 14 | Not measurable | |
| 15 | 5, 14 | 9 (15) |
| 16 | Not measurable | |
| 17 | Not measurable | |
| 18 | 5, 17 | 12 |
| 19 | 6, 17 | 11 |
| 20 | Not measurable | |
| 21 | 8, 17 | 9 |
| 22 | Not measurable | |
| 23 | Not measurable | |
| 24 | 11, 17 | 6 |
| 25 | Not measurable | |
| 26 | Not measurable | |
| 27 | 14, 17 | 3 |

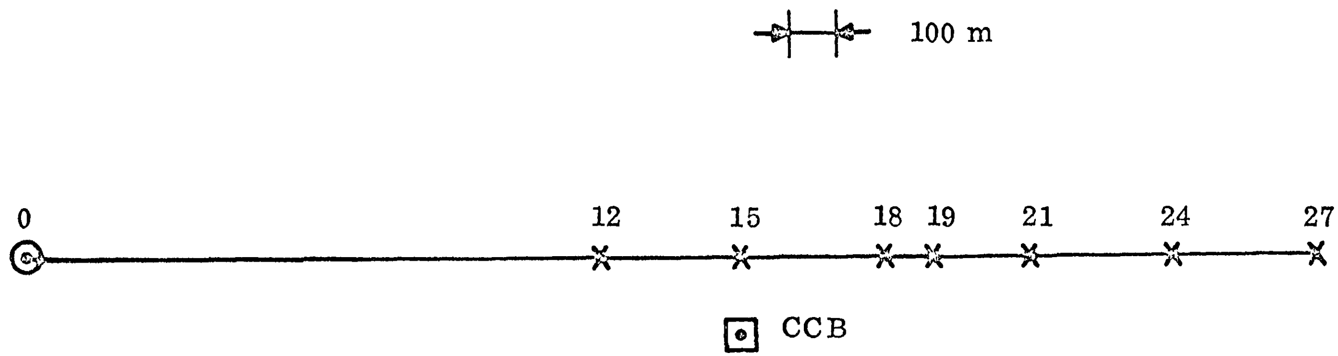
Figures between brackets indicate that a certain spacing can be obtained in two ways; the number gives the path length difference for the other, less favorable, possibility.

TABLE 2

CALCULATED WORST CASE PHASE ERRORS

| Variable | Assumptions | Phase Errors |
|---|---|---|
| LO frequency | Instabilities $5 \times 10^{-8}$<br>Path length inequality 1200 m | ± 0.3° |
| Path length with temperature | 1) Buried cable:<br>Temperature variations < 0.05 °C<br>Path length inequality 1200 m<br>Cable temperature coefficient $10^{-5}$/°C | ± 1.2° |
| | 2) Exposed cable:<br>Differential temperature variations < 2 °C<br>Equal cable length<br>Cable temperature coefficient $10^{-5}$/°C | ± 6.5° |
| Path length with cable pressure | Pressure instabilities $10^{-3}$ atm<br>Path length inequality 1200 m | ± 0.8° |
| Rotary joints | As measured | < 0.1° |
| VSWR | Changes of 0.015 | ± 0.5° |
| Amplifiers, frequency multipliers | Input power and ambient temperature stabilization adequate | ± 1° |

See also Fig. 4, Four Way Power Divider.




◉ Fixed in position element.

X Stations to put movable elements.

▣ Central control building.

FIG. 1 — NRAO INTERFEROMETER BASELINE CONFIGURATION, INCLUDING STATIONS FOR 85-3

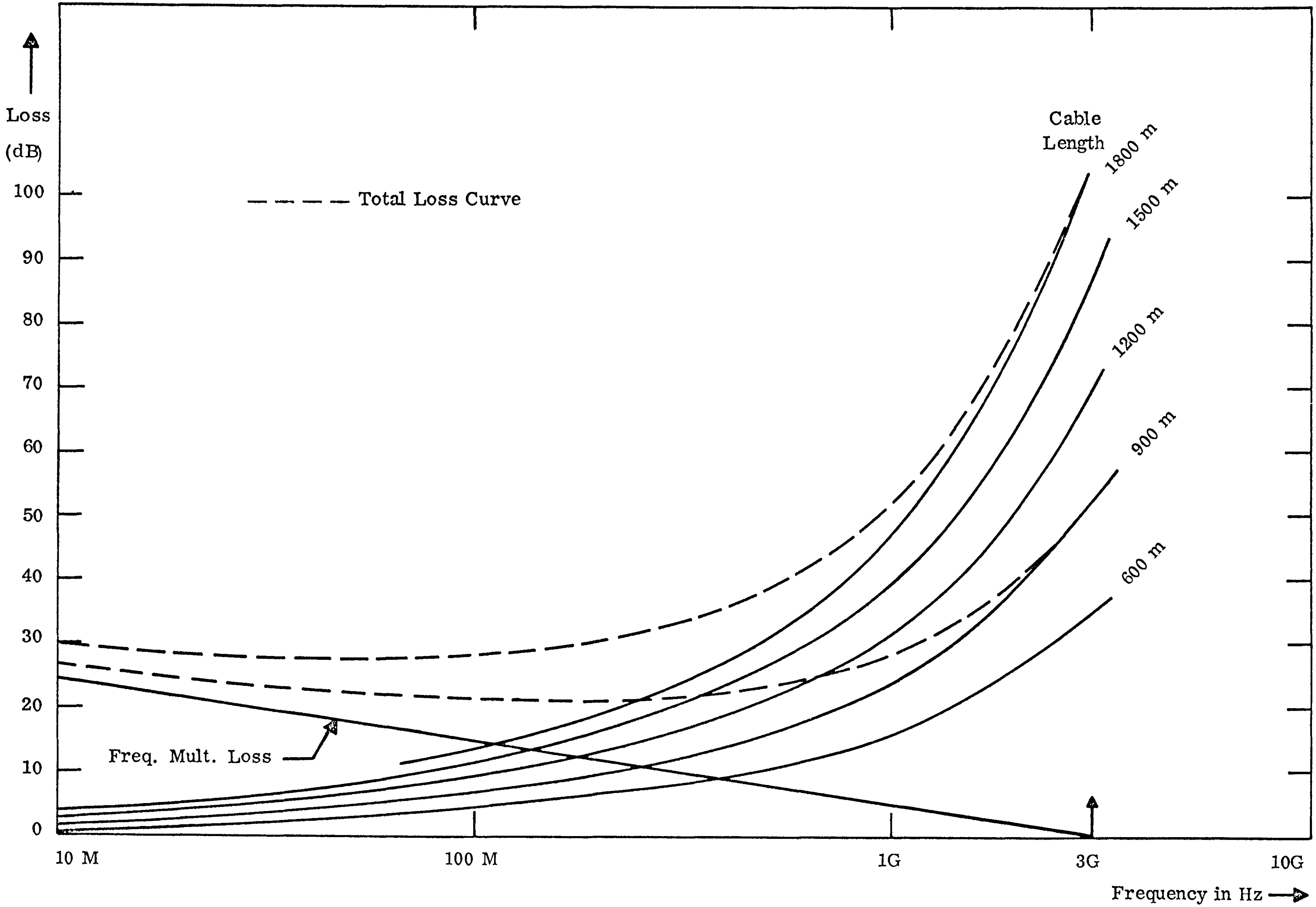



FIG. 2a — CABLE LOSS, MULTIPLIER LOSS AND TOTAL LOSS VS. FREQUENCY FOR PRODELIN SPIROLINE 1 5/8", 50 OHM CABLE

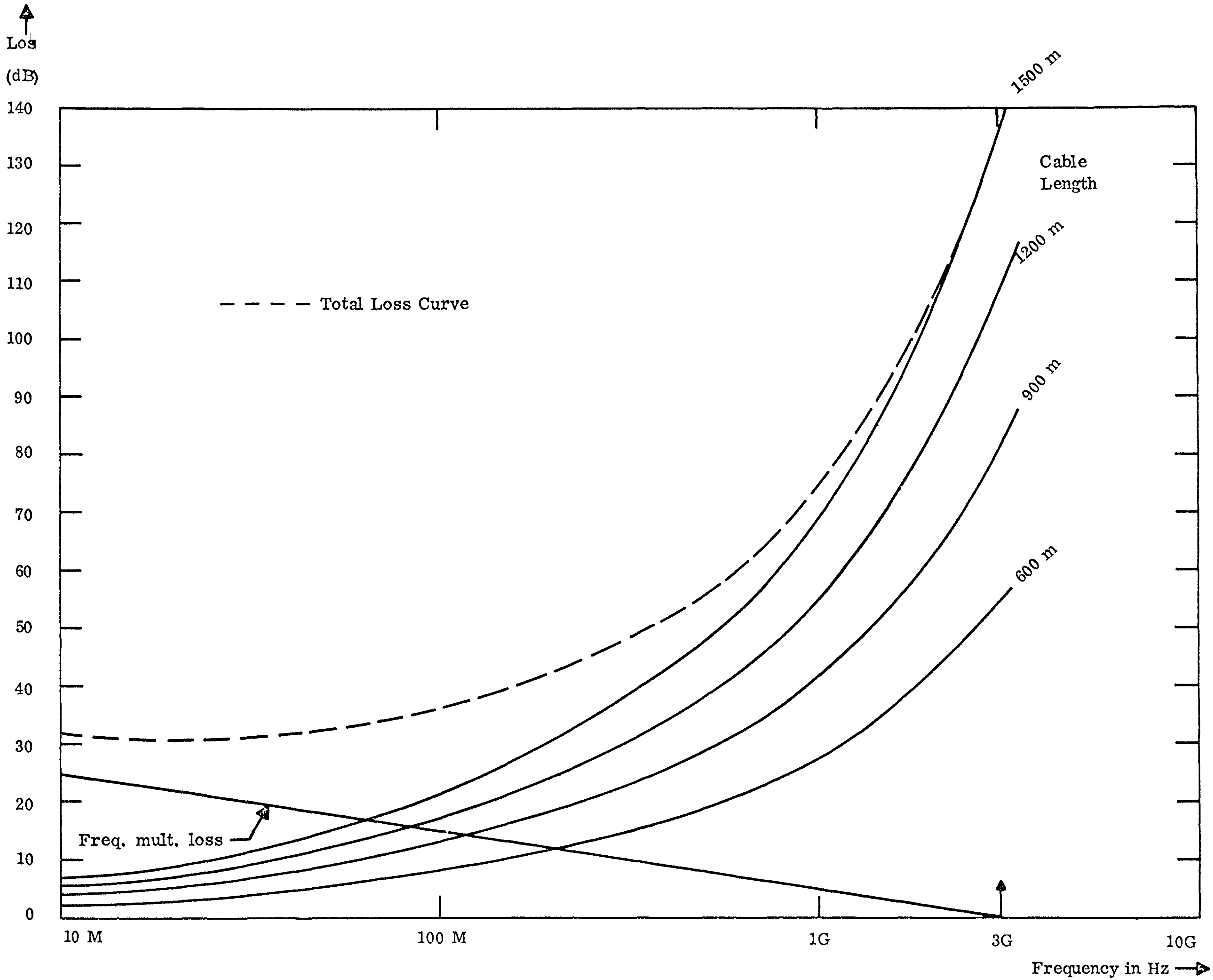



FIG. 2b — CABLE LOSS, MULTIPLIER LOSS AND TOTAL LOSS VS. FREQUENCY FOR PRODELIN SPIROLINE 7/8", 50 OHM CABLE

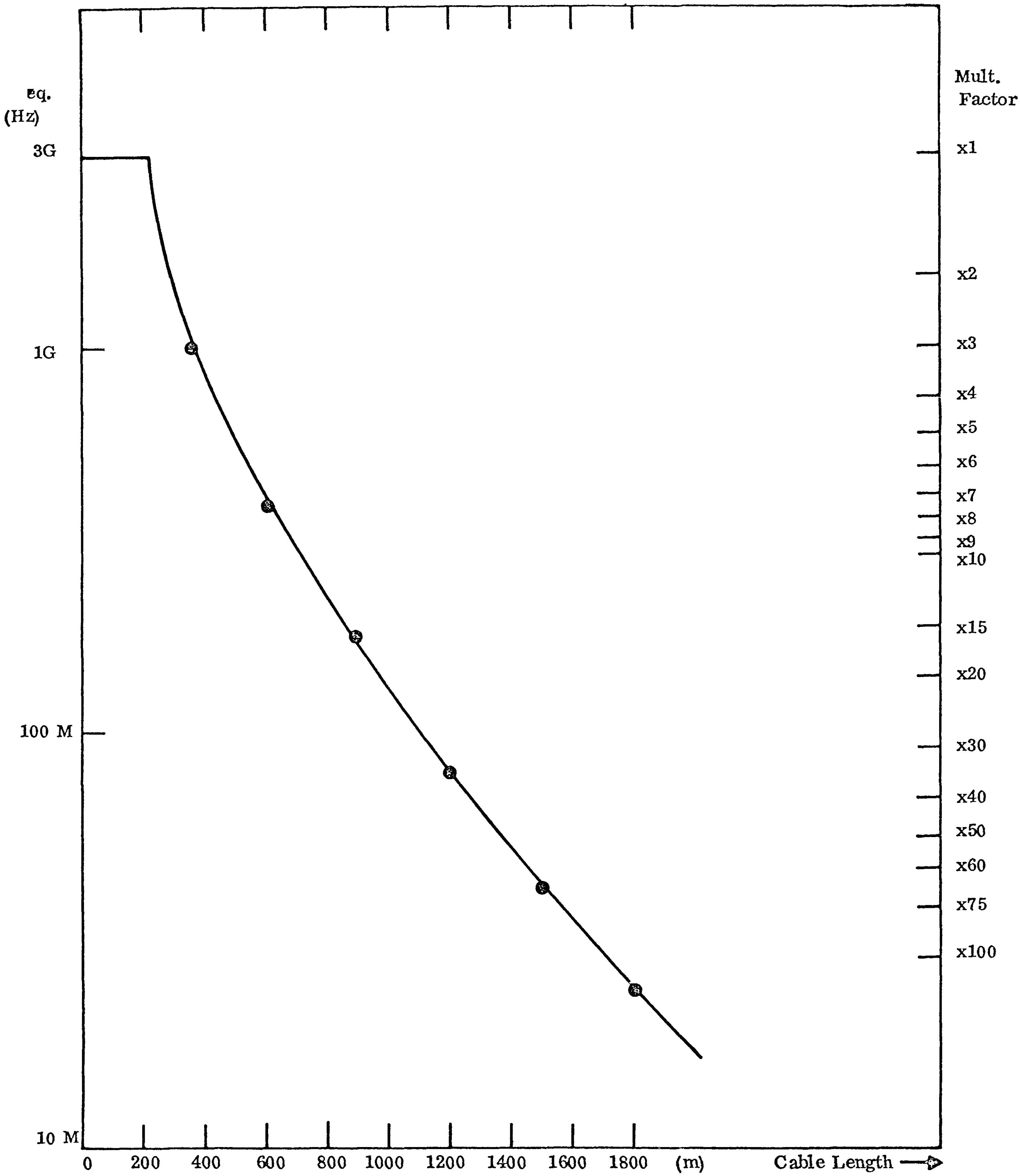
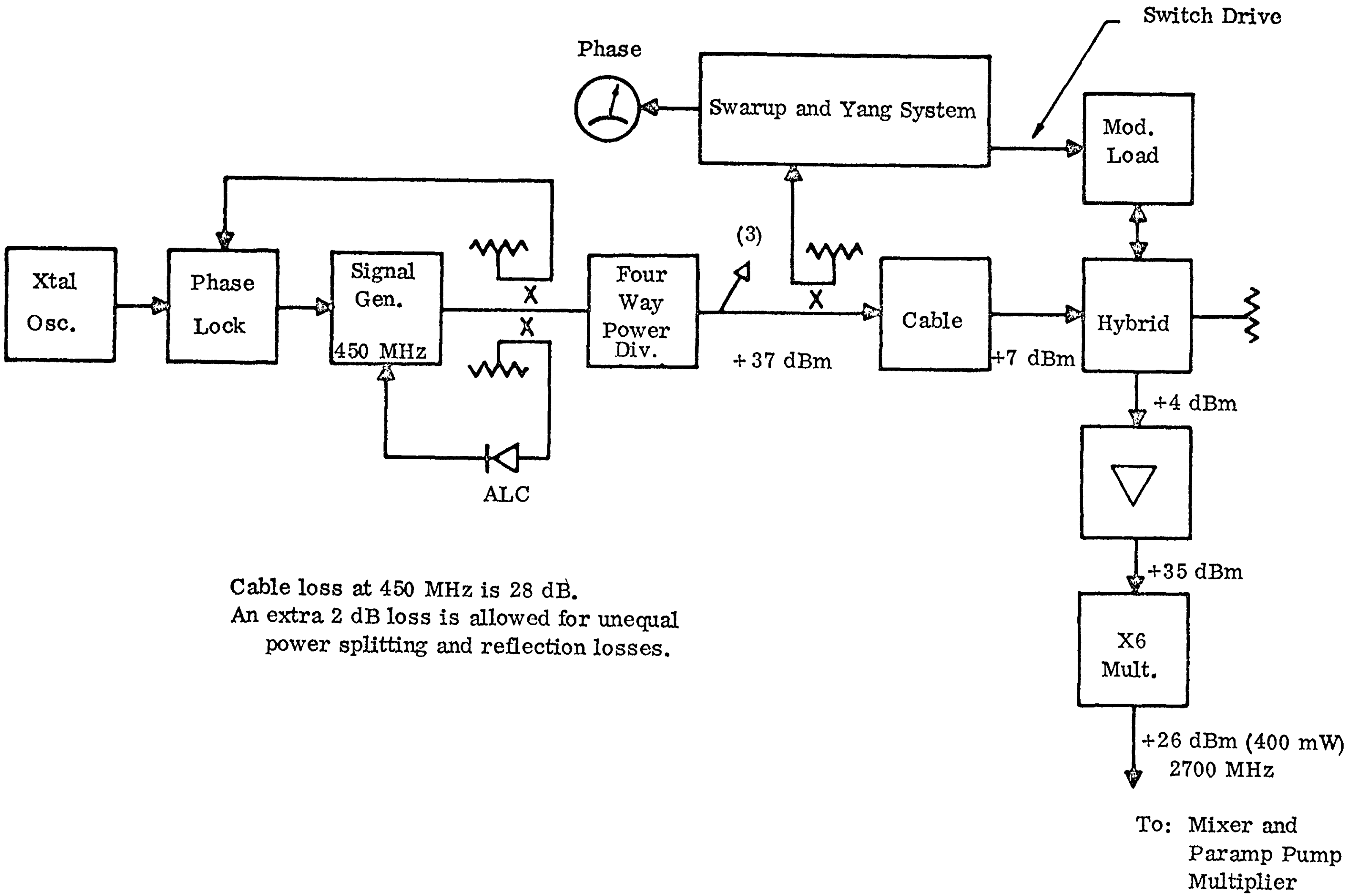



FIG. 3 — MINIMUM TOTAL LOSS TRANSMISSION FREQUENCY VS. CABLE LENGTH FOR PRODELIN SPIROLINE 1 5/8", 50 OHM CABLE




Cable loss at 450 MHz is 28 dB.
An extra 2 dB loss is allowed for unequal
power splitting and reflection losses.

FIG. 4 — POSSIBLE INTERFEROMETER LO DISTRIBUTION SYSTEM