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DESIGN OF A TWO ELEMENT INTERFEROMETER LOCAL OSCILLATOR SYSTEM

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Abstract

The problems of the local oscillator system are discussed starting with the basic requirements of the two element interferometer presently under construction at NRAO. Several system possibilities are discussed including the one which will be actually used. The reasons for the choice are elaborated and a block diagram can be found in figure 9.

To keep this report to a reasonable length, the analysis of the various systems has been drastically abbreviated — more detailed presentations should be available in the future when existing notes have been sufficiently organized. In addition, the switched system will be more thoroughly analyzed and will be presented in a final report.

This report is by no means complete nor final.

Page

I. Introduction

The interferometer system presently under construction at NRAO is in addition to being a working system for staff use a research tool for investigating the problems associated with multi-element antennas or systems composed of many antennas. This consideration dictates the need for versatility in electronic system interconnection.

The basic layout of the NRAO interferometer has been previously discussed [1]; therefore, we will not go into any great detail here, particularly with regard to the "astronomical" considerations. The system will observe a band of frequencies centered at 2695 Mc which will give an output at IF of 2 thru 12 Mc; double sideband technique is used [2], [1]. The present 85-foot antenna is to be used in conjunction with a movable 85-foot version which can be spaced 1200 m, 1500 m, 1800 m, 2100 m, 2400 m, or 2700 m from the present 85-foot antenna. If overall system phase uncertainty is $\gtrsim 10°$, serious ambiguities will occur; therefore, a phase lock system should be able to maintain phase stability to a small fraction of 10°.

The previous information is the basis for our design problems: the relatively high frequency in conjunction with the large spacings which range from about 11,000 λ to about 24,000 λ. The problems apparently have been simplified slightly by choosing to convert the received signal down to a lower frequency as shown in figures 1c and 1d. Figures 1b and 1d are refinements on 1a and 1c in that combining of signals is done at a central point. Since we have converted down to IF (2-12 Mc in the presently proposed system) in figures 1c and 1d, central combining as in figure 1d is not necessary. The problem now becomes one of phase locking the local oscillators (or local oscillator signals) at the two antennas; this is a simplification since a single frequency at 2695 Mc rather than a band of frequencies centered at 2695 Mc is involved. Figure 2 shows the three basic possibilities: (a) two oscillators which are phase locked, (b) a single local oscillator with a phase corrected path to the remote antenna, and (c) a single centrally located oscillator connected to each antenna by paths with identical characteristics.

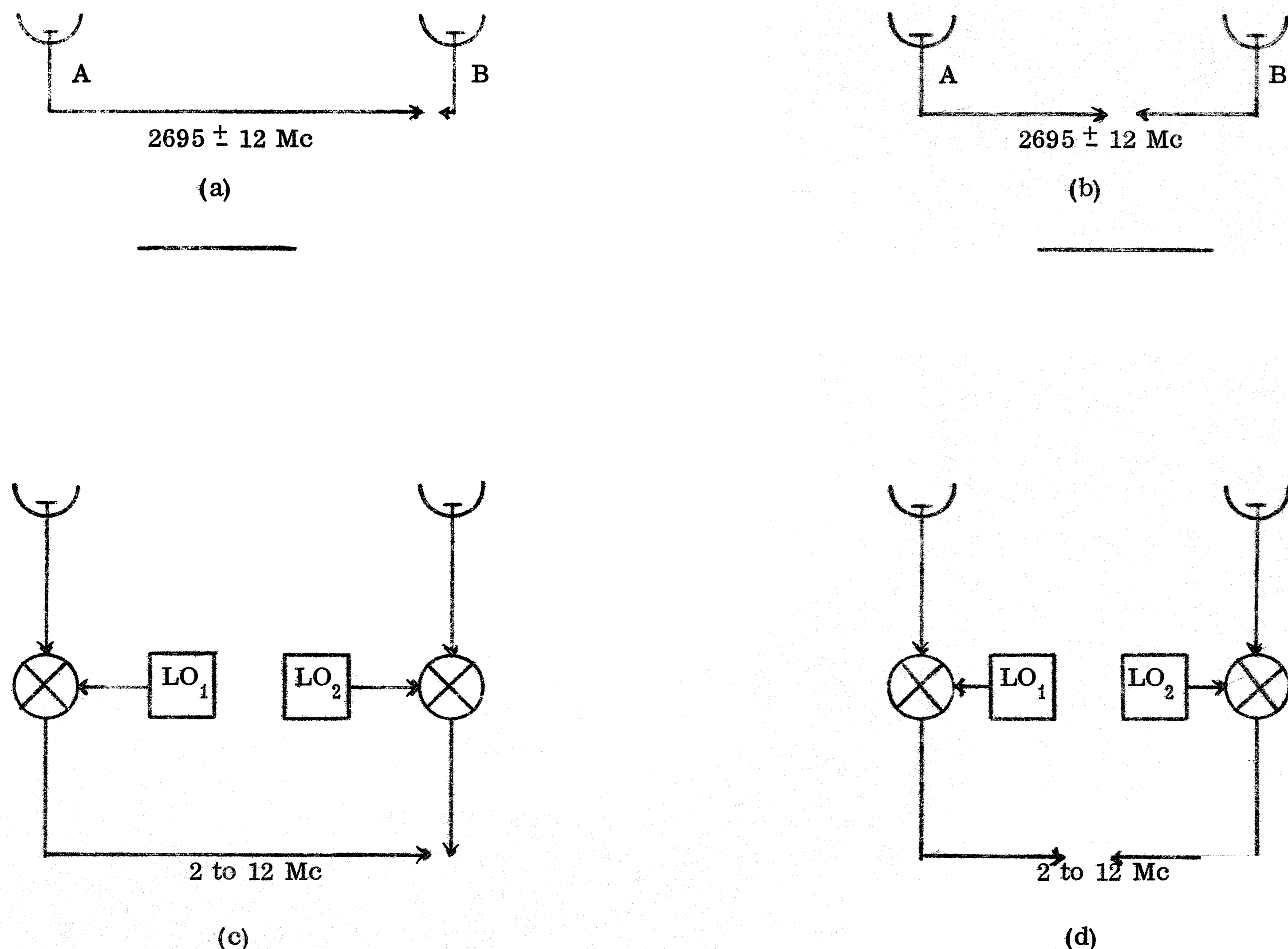


FIGURE 1

BASIC INTERFEROMETER LAYOUT

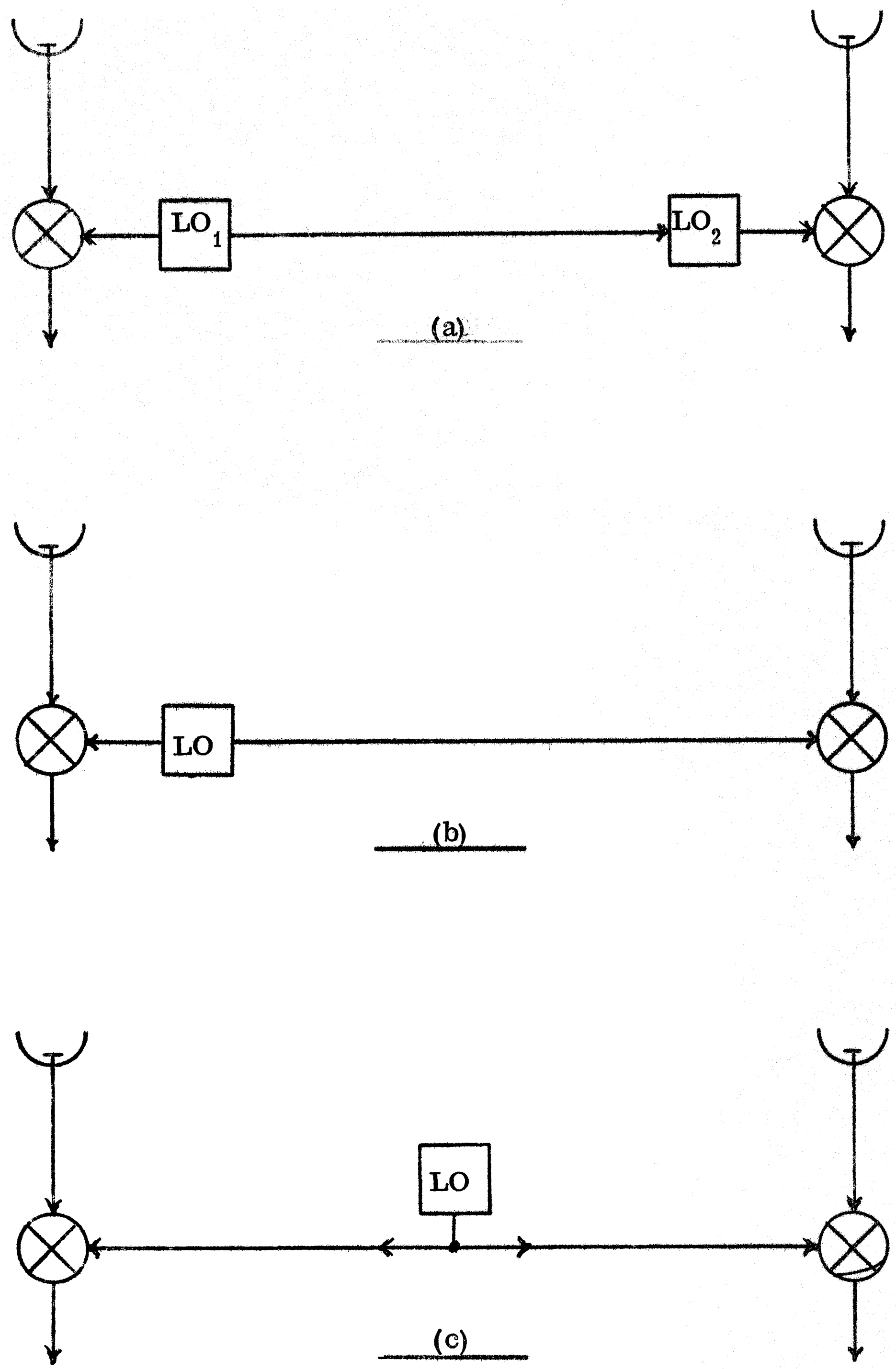


FIGURE 2

LOCAL OSCILLATOR PLACEMENT

Also, we have a choice from several possibilities for the connecting links: a cable system, a waveguide system, a surface-wave transmission line system, and a free space propagation system. All are subject to phase variations and large attenuations which present complications. Figure 3 shows the attenuations and phase changes which can be expected for certain cables and free space propagation. A cable system has advantages of slow phase variations and is probably easier to use over broad bandwidths; it is more practical when many antennas are used at relatively close spacings; it is not subject to interference and is not likely to interfere with other parts of the system. Some disadvantages of a cable system are its high cost (both the cable and installation are expensive) and because of large attenuations several expensive amplifiers are needed.

On the other hand, free space propagation links make use of a free transmission medium which has lower loss than cables; in addition, we are provided with possibilities of accurate measurement of antenna separation. Atmospheric phase variations are thought to be relatively slow but multi-path effects are also important and may contribute apparent fast phase fluctuations. The combined effect of multi-path and atmospheric variations is being measured in a current experiment at NRAO. In addition, this system is an interference generator and receiver and becomes impractical for an array of many relatively closely spaced antennas.

Waveguide, like rigid cable, requires many connectors and is difficult to install; it is subject to large phase changes and attenuation changes when there are temperature variations. Some of these problems are circumvented by overmoding but other difficulties arise which become practical limitations.

Surface-wave transmission line is another possibility — it exhibits low loss which is comparable to conventional waveguide but exposure to the atmosphere would give large phase fluctuations from dirt, moisture, temperature changes, and incident radiant energy changes. Since approximately 90% of the transmitted energy is within a radius of one wavelength, a system utilizing large underground conduit could be used to obtain a stable environment; major contributors to loss would be the supports and line sag.

Therefore, it appears that a cable system should be constructed initially.

Frequency	2695 Mc	$\frac{2695}{2}$	$\frac{2695}{4}$	$\frac{2695}{8}$	10 Mc
Attenuation of 1 5/8" cable					
Per 100'	1.6 db	.95 db	.62 db	.43 db	.07 db
1200 m	63	37.4	24.4	16.9	2.76
2700 m	142	84.2	54.8	38.1	6.2
Attenuation of 1/2" cable					
Per 100'	4.4 db	2.9 db	2.0 db	1.4 db	.23 db
1200 m	173	114	78.8	55.1	9.05
2700 m	---	---	---	---	20.4
Maximum phase variation (-10 °C to + 30 °C)					
Spir-O-line/100'	6°	3°	1.5°	.75°	.0223°
Styroflex/100'	36	18	9	4.5	.134
Spir-O-line, 1200 m	236	118	59	29.5	.85
Styroflex, 1200 m	1416	708	354	177	1.91
Spir-O-line, 2700 m	532	266	133	66.5	5.1
Styroflex, 2700 m	3192	1596	798	399	11.5
Gain of 10' dish	36 db	29 db	23 db	18 db	---
Free space loss, 1200 m	90	83	74	66	---
Free space loss, 2700 m	95	87	78	70	---

Figure 3

II. The California Institute of Technology Interferometer System [2]

It has been suggested that possibly a system similar to the one used by the California Institute of Technology at the Owens Valley Radio Observatory could be utilized by NRAO. Figure 4 shows a block diagram of the receiver; figure 5 shows a block diagram of the phase lock system.

It is obvious that the system is dependent on mirror image cable and/or radiated links. The minimum spacing to be used at NRAO is 1200 m and as shown in figure 6, there will be spans of about 600 m from the reference signals. From the information of figure 3 it is easy to see that at ≈ 2695 Mc there could be as much as 64° difference in the received signals when the best cable is used (for a difference of 3 °C or greater in cable temperatures). The 2700 m spacing would give a proportionally greater amount. Of course, these are maximums and if the cables are buried, temperature changes can be held to a minimum. Similar calculations show that for maximum spacing (2700 m), the low frequency reference is subject to a maximum difference of ≈ 0.10°/Mc which is acceptable for low frequency references in the low megacycle region. As previously mentioned, a radiated link is subject to other perturbations and would not be as stable as a good cable system.

Therefore, we can conclude that although a good non-phase locked cable system could be used in a limited observation program, more extended programs would require phase locking of the high frequency reference signals at the two antennas; any low frequency references present no problems of this nature.

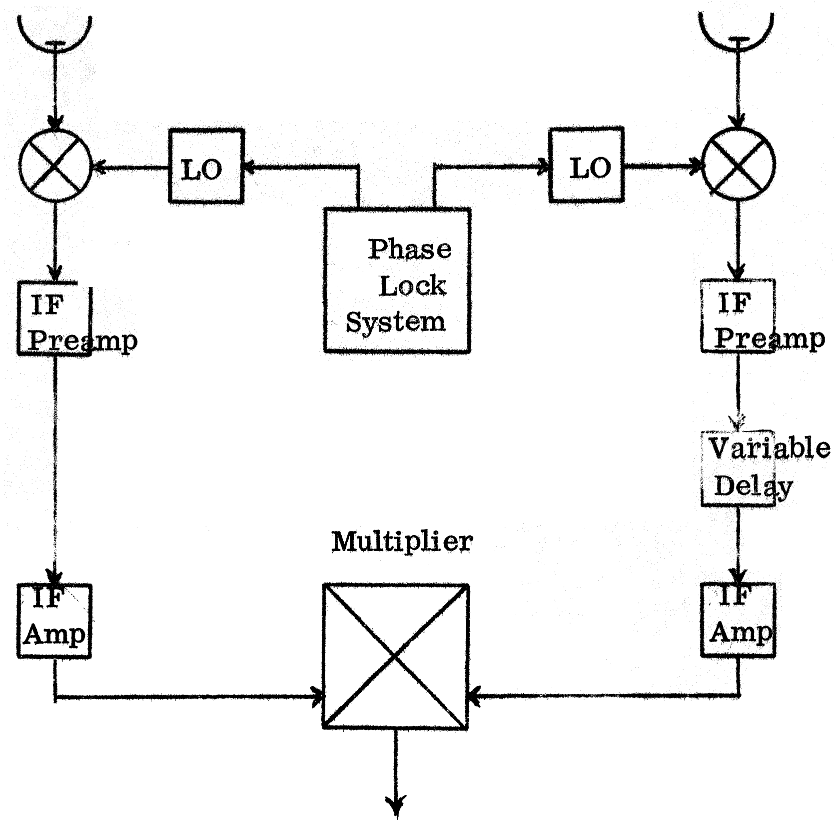


FIGURE 4

CAL. TECH RECEIVER BLOCK DIAGRAM

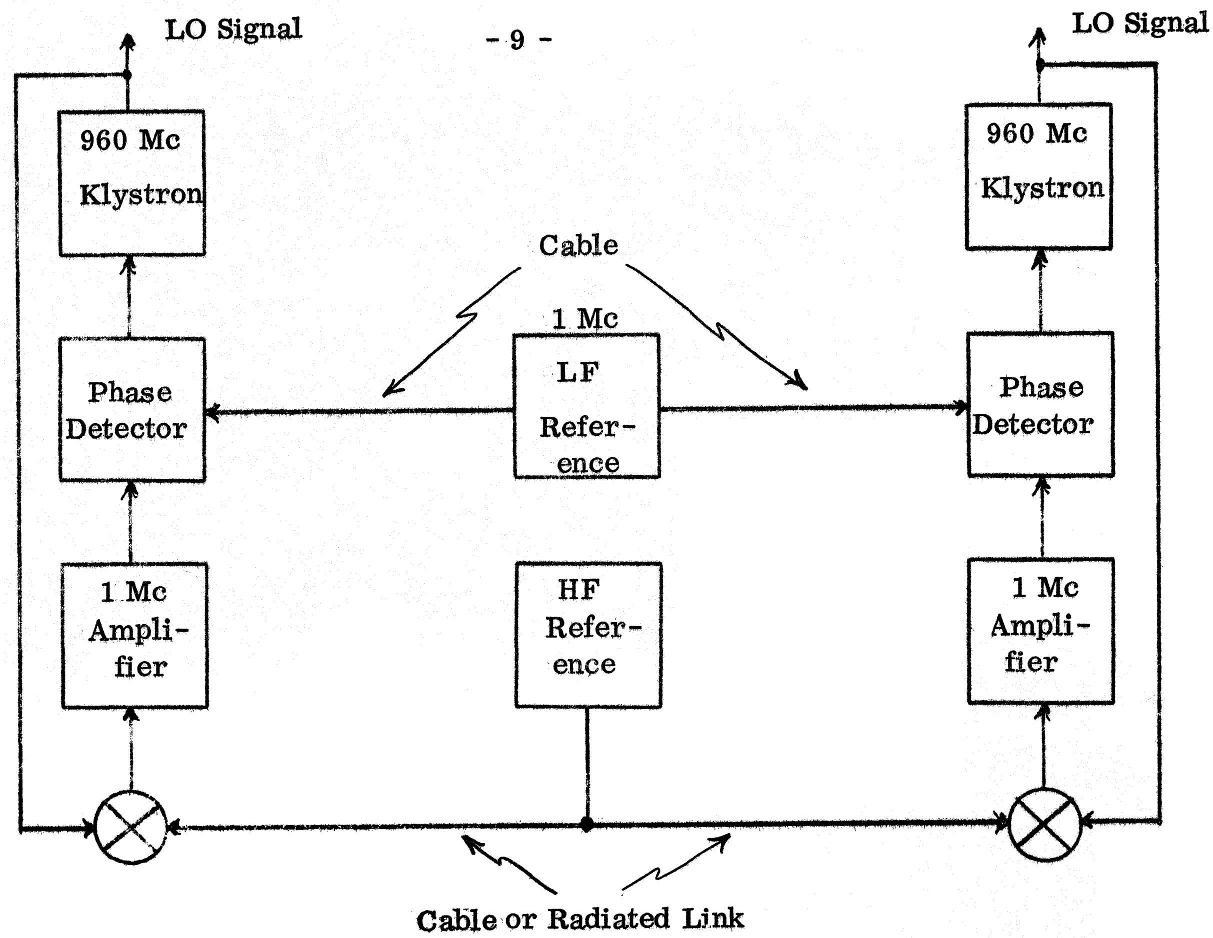


FIGURE 5

CAL. TECH PHASE LOCK SYSTEM

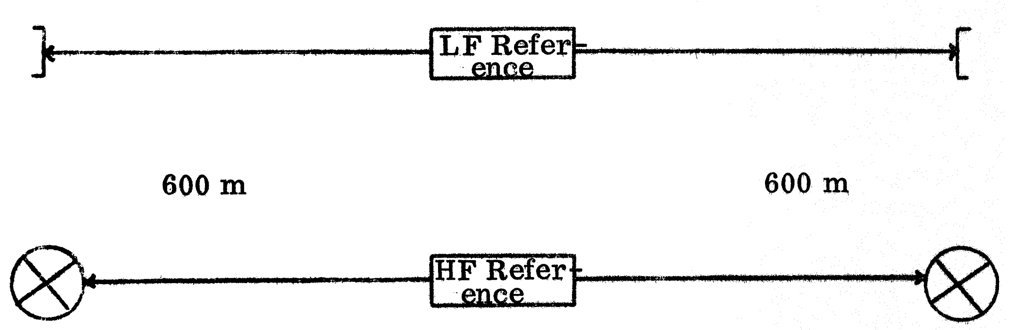


FIGURE 6

NRAO SPACING

III. Phase Correction Loop Design

Each antenna site requires a local oscillator signal of 2695 Mc which should have fixed and/or known phase relations with each other. Also, it is easily seen that unless the transmission paths between a reference source and each site are identical in length, a frequency perturbation would cause a relative phase change in proportion to the frequency and length difference.

$$\text{Frequency stability} = F_S = \frac{d}{360n}$$

where d = maximum phase change in degrees

n = number of wavelengths at f_o (center frequency).

Example: Path length = 30,000 λ = n

$$d = 0.1°$$

$$F_S = \frac{0.1}{360 \times 3 \times 10^4} \approx 1 \times 10^{-8}$$

This gives us the order of stability required if the interferometer system is fed at one end when maximum spacing (2700 m) is used with a "passive" cable system or a phase correcting system which has a response time slower than the changes induced by the reference source variations.

We should also note that, depending on the overall system design and the nature of the observational program, even if central spacing of the reference is used, there would be phase fluctuations of equal amounts at both antennas relative to another source at a fixed position in proportion to the frequency variations and length of path between an antenna and the reference which might be of concern in the experiment.

The actual connecting link must transmit a reference signal to the remote site and return information about the remotely received signal which can be used for comparison purposes at the home site. Obviously, we have to either use exactly the same link for the return transmission or use a link with known characteristics. These characteristics can be determined if they have a known relationship with the forward path and do not have to be independently available. Therefore, the possibilities of what becomes multiplexing can be listed as follows:

A. Physical.
   1. Directional discrimination.
   2. Multiple cables.

B. Frequency.
   1. Remotely received signal is changed in frequency before it is returned.

C. Time.
   1. A path is used alternately for the two propagation directions.

A directional discrimination system is a straightforward approach which is basically totally dependent on the directional discrimination characteristics of available components. A multiple cable technique basically depends on matched cables.

The frequency translation schemes usually depend on a known relationship between transmission characteristics at two different frequencies; in addition to frequency discrimination, directional discrimination can also be used to separate the transmitted and received signals.

Time sharing appears to have attractive possibilities but is faced with limitations on maximum switching speeds so that "stable state" phase comparisons can be made while phase stability is maintained.

To correct for phase variations we must be able to measure them; hybrid tees are quite suitable for this purpose. If amplitude variations are a problem, two such phase detectors can be used with a 90° phase shift included in one leg of one of the phase detectors as shown in figure 7. This 90° can easily be obtained at microwave frequencies with a short slot hybrid (3 db coupler).

A fundamental difficulty arises in phase measurement — ambiguity. This ambiguity generally appears as a 180° uncertainty; this is usually caused by a phase measuring system correcting at half the length of the measurement path. It is possible to eliminate the ambiguity by operating the measuring system at half the operating frequency and doubling frequency at each antenna position. The disadvantage of this scheme is that the system phase error is approximately doubled. If the system has a known relationship between transmission characteristics at different frequencies, a lower frequency (most conveniently $f_{LO}/2$) can be transmitted from one site to the other in addition to f_{LO} so that the better accuracy of measurement at f_{LO} can be utilized; this half frequency is then used to resolve the ambiguity. It is possible to frequency divide with accuracies of about 3° which is sufficiently accurate for 180° discrimination; the disadvantages are additional amplifier requirements and transmission characteristics differences.

Phase correction can now be made by one or a combination of several different ways — mechanical, ferrite phase shifter, varactor phase shifters, or variation of TWT amplifier voltages such as the helix voltage. In general, any correcting unit should be located in a closed loop so that setting accuracies are not important; this is particularly true of any active devices.

Another area of consideration is lobe rotation; this can be accomplished in two basic ways. The most obvious way is to continuously add delay into the signal path of the proper antenna — because this is of the order of 11,000 λ to 24,000 λ, this method is not very practical. The other method is one used at the California Institute of Technology and outlined in figure 8. During operation, the phase shifter "P" is rotated at a rate required to give the necessary frequency difference between f_{LO_1} and f_{LO_2}.

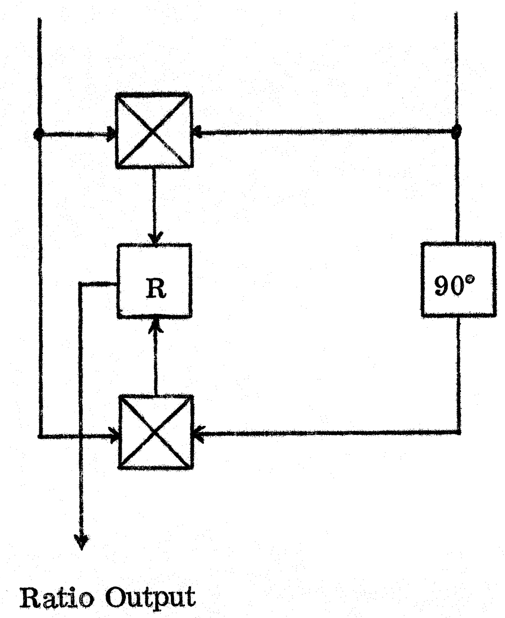


FIGURE 7

NON-AMPLITUDE SENSITIVE PHASE DETECTOR

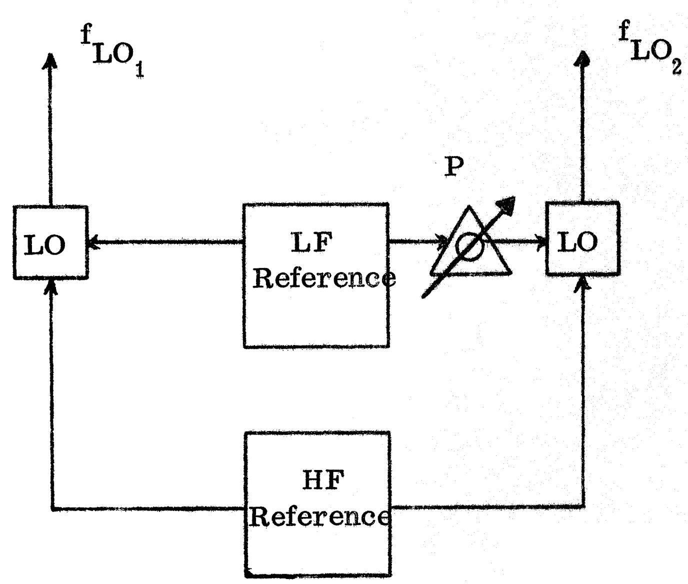


FIGURE 8

LOBE ROTATION

IV. Proposed Systems

Proposed systems and sub-systems have been diagrammed in figures 9 thru 23; they can be listed as follows:

1. Switched (figure 9).
2. Double sideband (figure 10).
3. Single sideband, frequency translated (figures 11, 12, 13).
4. Counting (figures 14, 15).
5. Single sideband reflected (figures 16, 17, 18).
6. High order multiplier (figures 19, 20).
7. Placement of system component parts at each site with a switched, lobe rotated system (figure 21).
8. Front-end amplifier phase compensation (figure 22).
9. Line amplifiers (figure 23).

The design considerations of each of the above systems is discussed below:

1. Of primary concern in a switched system is the switching rate. The minimum rate is determined by the rate of change of the measured variables; the maximum rate is determined by either physical or state-of-art considerations or a combination of both.

In our case, the minimum rate is determined by the maximum rate of change of phase in the connecting link; a buried cable link appears to be well adapted to providing a slow changing system. The maximum rate will be determined by the transmission time between the two sites at their maximum separation plus the time necessary for comparison and possibly the maximum switching rate obtainable with microwave switches.

The basic mode of operation of a switched system is as follows:

LO ⟶ cable No. 1

cable No. 2

Site A Site B

Neglecting transit times, half the time the local oscillator signal is connected to both cables at site A and the phase difference is measured at site B. The other half of the time the cables are connected together at site B and a phase comparison is made at site A.

Basic mathematical analysis:

Let LO output be $\cos \omega t$

ϕ_1 = phase shift of cable No. 1

ϕ_2 = phase shift of cable No. 2

T_1 = time cables are connected together at A

T_2 = time cables are connected together at B

During T_1, $\cos(\omega t + \phi_1)$ is compared with $\cos(\omega t + \phi_2)$ at B. A simple phase comparison gives us $\cos(\phi_1 - \phi_2)$.

During T_2, $\cos \omega t$ is compared with $\cos(\omega t + \phi_1 + \phi_2)$ at A. A phase comparison gives us $\cos(\phi_1 + \phi_2)$.

The $\cos(\phi_1 - \phi_2)$ and $\cos(\phi_1 + \phi_2)$ can easily be combined since the remote comparison $\cos(\phi_1 - \phi_2)$ is of low frequency and can be transmitted directly or digitally to A using suitable time delays in the system.

When the transit time of the cables is considered, we find that comparison times are reduced accordingly. Since the maximum spacing will be 2700 m, we have a cable length with about a 10 μsec delay. A rough figure for the maximum switching frequency is $F = (T_1 + T_2 + 4\delta)^{-1}$ or $(2T + 4\delta)^{-1}$. If "steady state" conditions can be obtained in 10^5 cycles, at $\approx$ 2700 Mc, $T \approx 35\ \mu$sec,

$$F = \frac{10^6}{(70 + 40)} \approx 9 \text{ kc.}$$

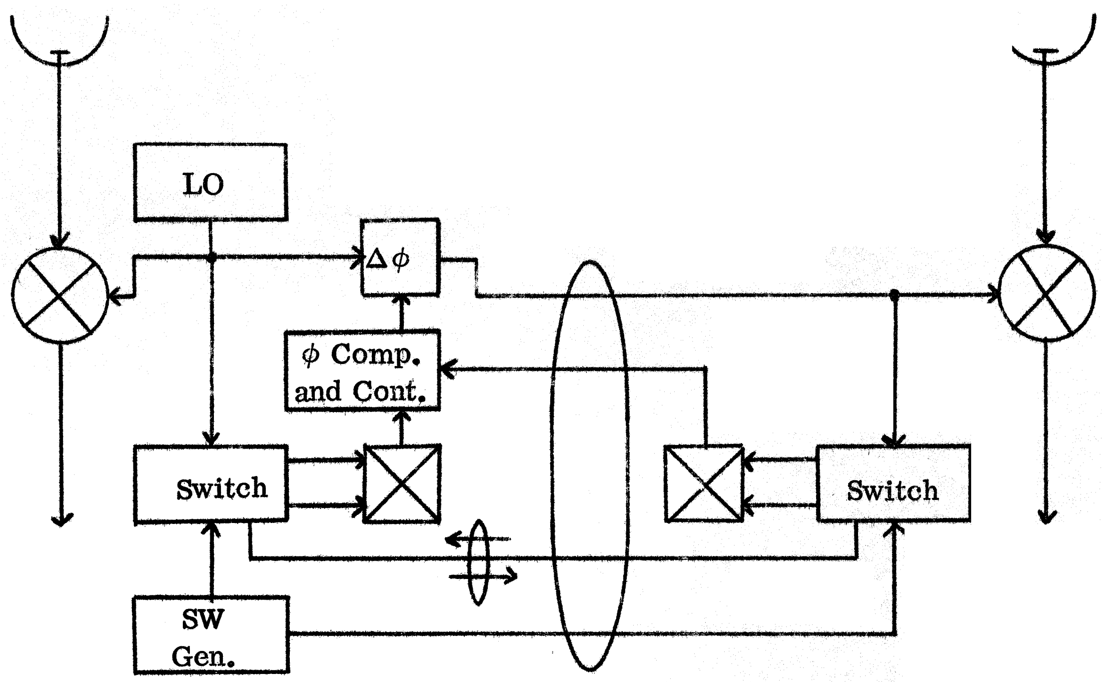
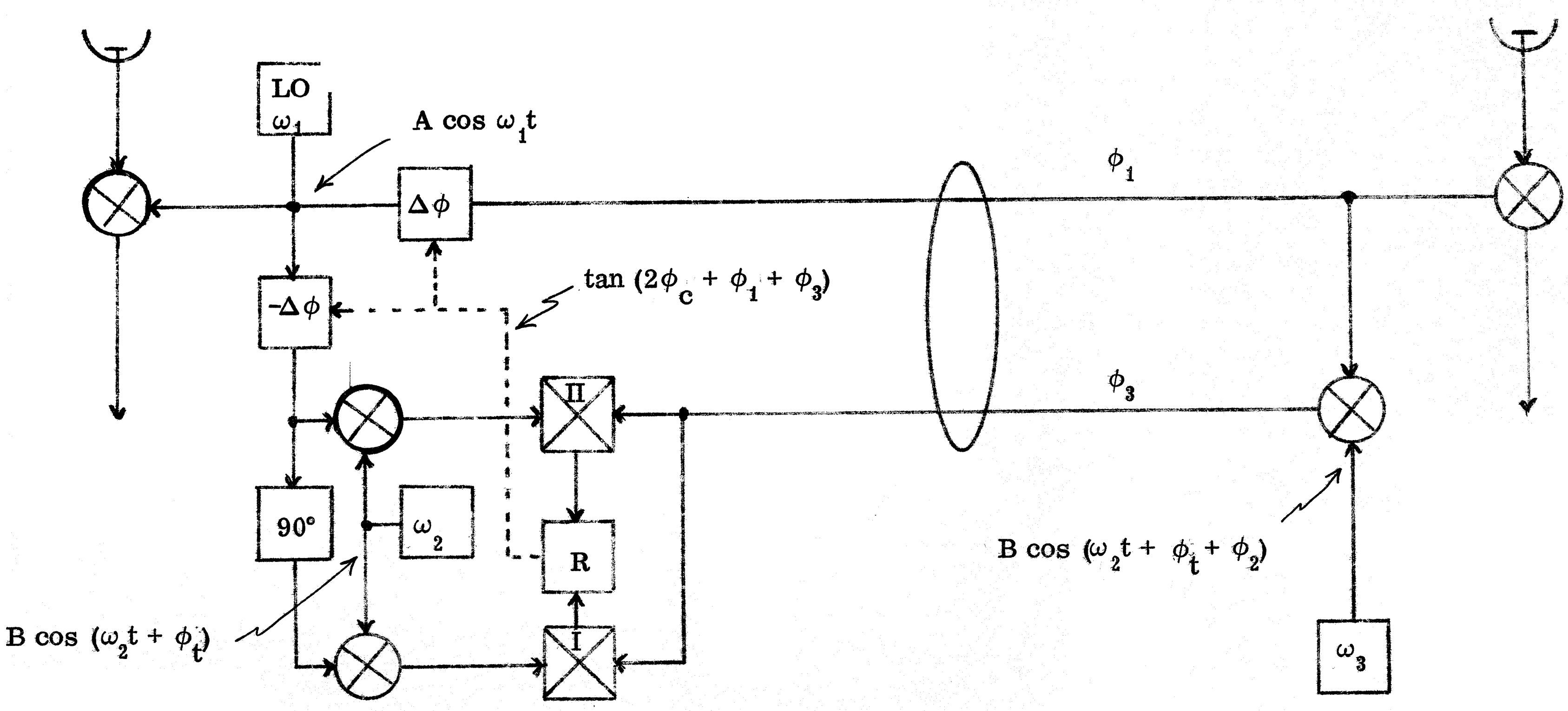


FIGURE 9

SWITCHED SYSTEM



$\omega_3 \approx \omega_2$ $\phi_c = \Delta\phi$

If same cable is used, $\phi_1 = \phi_3$ which is a necessity.

FIGURE 10

DOUBLE SIDEBAND SYSTEM

A good cable system with expected thermal time constants would have about 24° maximum phase shift per hour (.00667°/sec). Therefore, a switching rate as low as 1 c/s would be sufficient. This is fortunate because the microwave switches used must impart the same transmission characteristics to the link for both directions of transmission — suitable switches tend not to be capable of high switching rates.

2. Basic operation of the double sideband system is to transmit the local oscillator signal to the remote antenna and to return the two sidebands produced by a balanced mixer; the only filtering required here is to suppress the local oscillator signal (and any generated harmonics).

The output of the ratio circuit "R" $= \frac{II}{I} = \tan(2\phi_c + \phi_1 + \phi_3)$

where $II = A^2B^2 \sin(2\phi_c + \phi_1 + \phi_3)\cos(\phi_2 + \phi_4)$

and $I = A^2B^2 \cos(2\phi_c + \phi_1 + \phi_3)\cos(\phi_2 + \phi_4)$

with the assumption that the velocity of propagation is the same for all frequencies of concern.

$$\text{Generally, } II = \frac{A^2B^2}{2}[\sin(2\phi_c + \phi_1 + \phi_3 + \phi_2 + \phi_4) + \sin(2\phi_c + \phi_1 + \phi_3 - \phi_2 - \phi_5)]$$

$$I = \frac{A^2B^2}{2}[\cos(2\phi_c + \phi_1 + \phi_3 + \phi_2 + \phi_4) + \cos(2\phi_c + \phi_1 + \phi_3 - \phi_2 - \phi_5)]$$

where

ϕ_c is the phase correction.

ϕ_1 is the LO signal phase shift in the forward direction.

ϕ_3 is the LO signal frequency phase shift in the return direction.

ϕ_2 is the phase difference between ω_2 and ω_3.

$\phi_3 + \phi_4$ is the phase shift of the returned upper sideband.

$\phi_3 - \phi_5$ is the phase shift of the returned lower sideband.

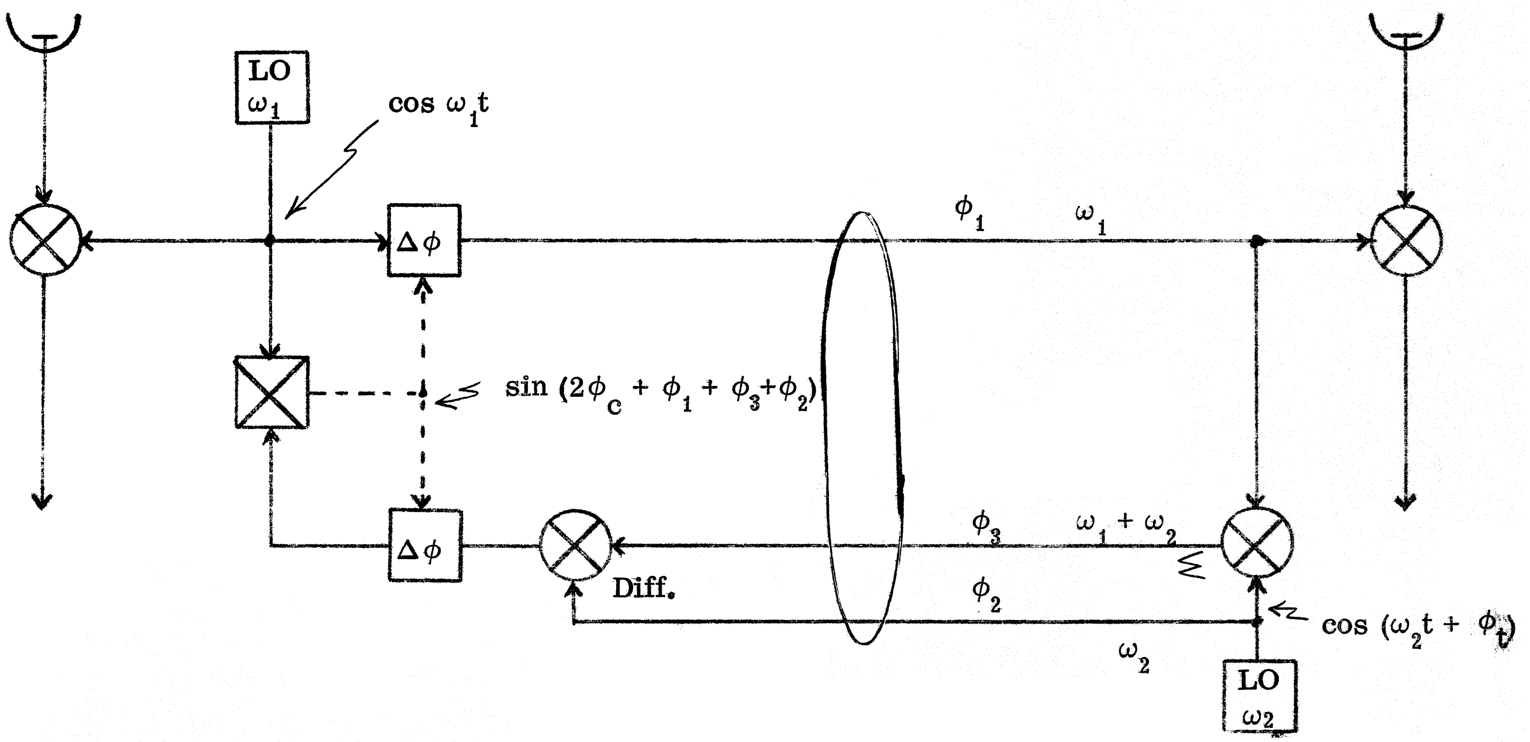


FIGURE 11

SINGLE SIDEBAND SYSTEM, FREQUENCY TRANSLATED

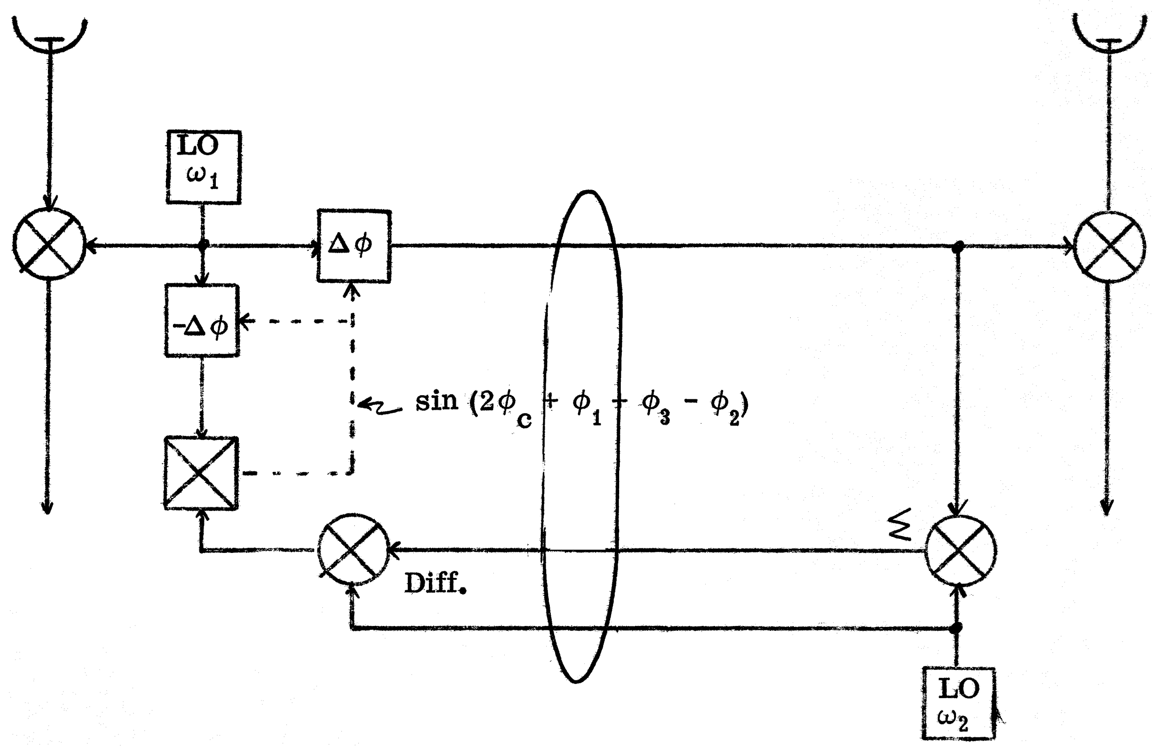
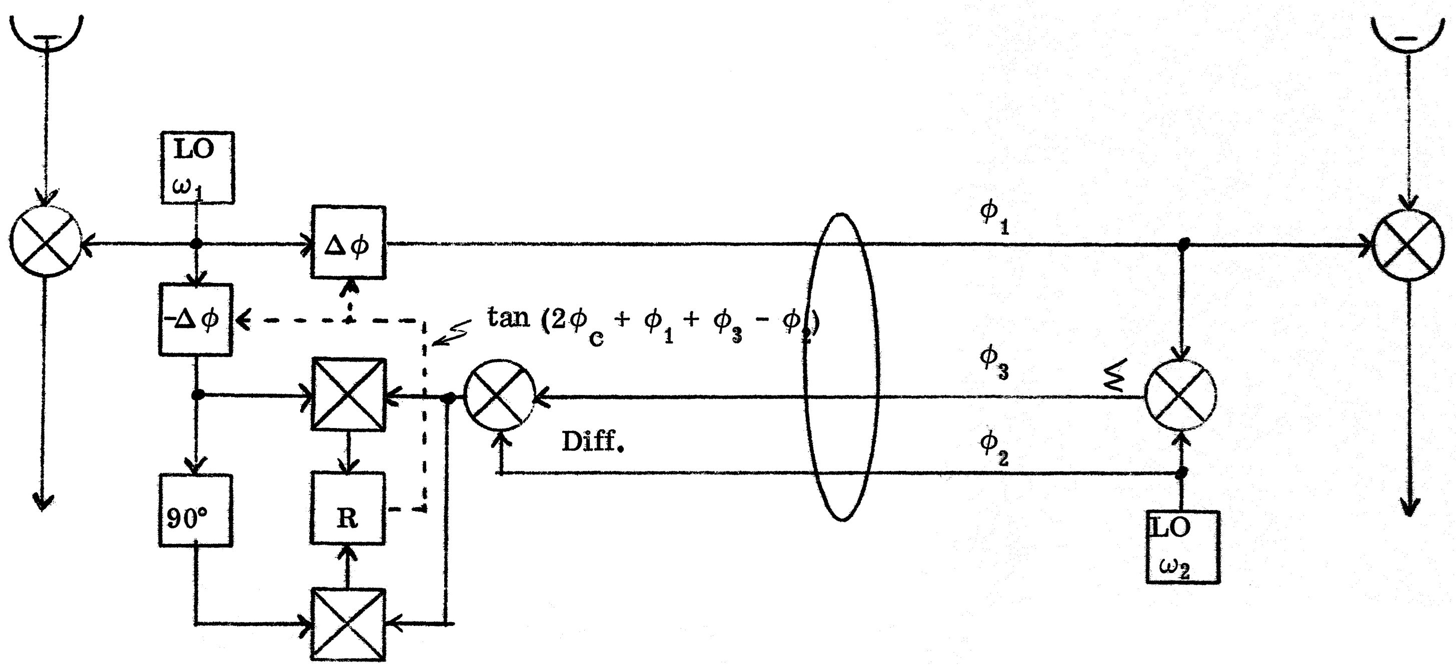


FIGURE 12

SINGLE SIDEBAND SYSTEM, FREQUENCY TRANSLATED



One necessary condition is that

$(\phi_3 - \phi_2) = \phi_1$

FIGURE 13

SINGLE SIDEBAND SYSTEM, FREQUENCY TRANSLATED

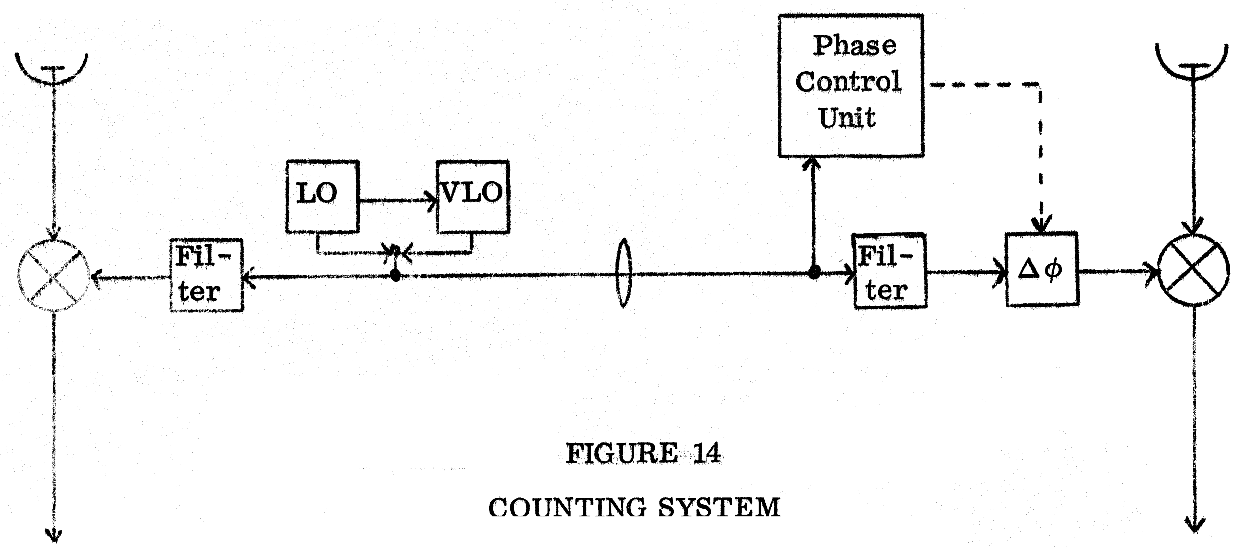


FIGURE 14

COUNTING SYSTEM

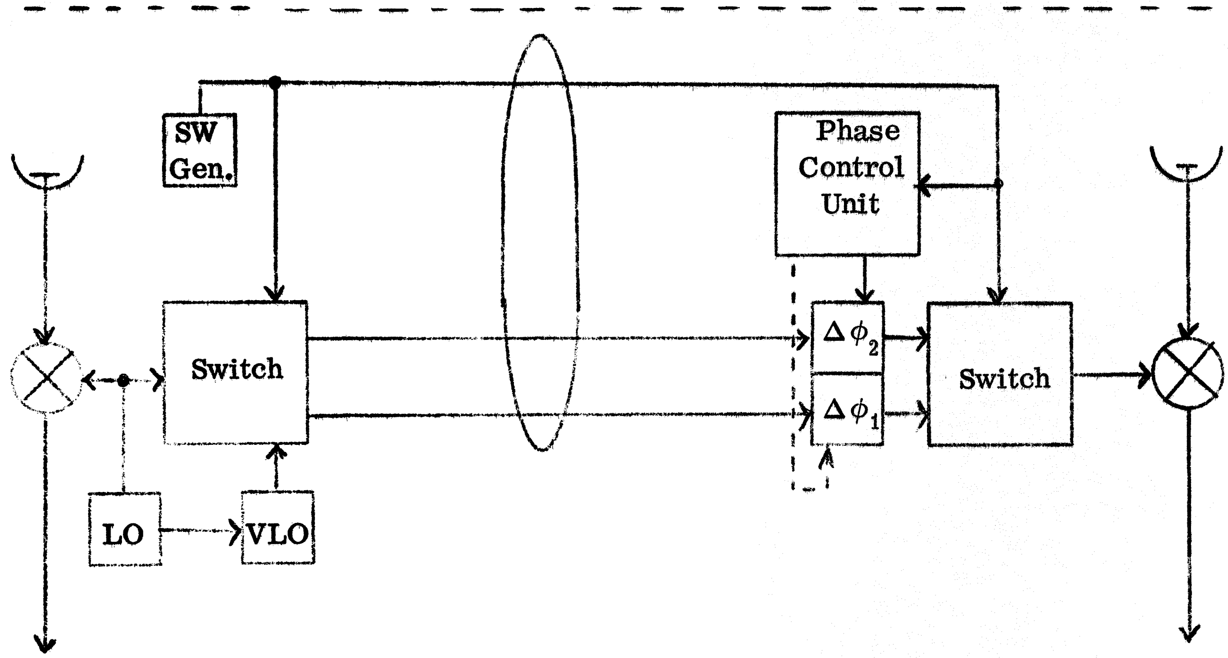


FIGURE 15

COUNTING SYSTEM

3. The basis for the operation of the single sideband frequency translation system is to frequency translate the returned signal so that frequency discrimination can be used in addition to directional discrimination. Figure 12 is a variation of figure 11, whereas figure 13 is a variation which eliminates some amplitude perturbations and shows this system's similarity to the double sideband arrangement.

This system also requires a frequency independent velocity of propagation besides keeping $(\phi_3 - \phi_2) = \phi_1$. Filtering is necessary to remove the other sidebands in addition to the local oscillator signal.

4. The counting system is based on the principle that the electrical length (number of λ) of a path is based on the frequency, the velocity of propagation and the physical length. Therefore, the number of λ at a given frequency can be determined if the number of cycles are counted as the frequency is changed between two known frequencies.

Let N = number of observed cycles

1 = physical length

f_1 = the higher frequency

f_2 = the lower frequency.

$$N = \frac{1}{\left(\lambda_{f_2} - \lambda_{f_1}\right)}$$

$$1 = \left(\lambda_{f_2} - \lambda_{f_1}\right) N$$

Number of wavelengths at $f_2 = n = \dfrac{1}{\lambda_{f_2}}$

$$n = \left(\frac{\lambda_{f_2} - \lambda_{f_1}}{\lambda_{f_2}}\right) N$$

If f_2 and f_1 and their ratio can be accurately maintained, the problem becomes one of knowing the variations (if any) of the velocity of propagation. To be useful for phase locking it must be possible to count fraction of cycles accurately; for example, 1° accuracy would require a count of:

$$360\, n \text{ or } 360\left(\frac{\lambda_{f_2} - \lambda_{f_1}}{\lambda_{f_2}}\right) N$$

It is not certain that this technique could be used for phase locking but it could be used to determine the number of λ of a path — this would be most useful between feed horns via free space to determine the exact number of λ separation.

5. The single sideband "reflected" system is probably the simplest but since it depends on a "reflected" signal, it is very susceptible to VSWR changes. When repeater amplifiers become involved, this type of system is out of the running when our accuracy requirements are considered.

6. The high order multiplier system relies on the feasibility of multiplication of some relatively low frequency at each antenna site. The reference frequency could either be so low that it would not contribute an important amount of phase shift while being transmitted between sites or a relatively simple phase correcting circuit could be used. Figure 20 shows that the overall operation is basically dependent on the ability to divide frequency and maintain phase since a simple multiplier circuit would simply multiply the phase error.

Figure 21 shows the placement of system component parts at each site for the switched system with lobe rotation capabilities exclusive of any components necessary to maintain phase stability of a front-end amplifier; a possible scheme for this is shown in figure 22. It should be noted that all diagrams are of a general nature and do not show all the necessary amplifiers or filters, etc.

The line amplifiers used are dependent on the actual configuration — several possibilities are shown in figure 23. Figure 23a uses two amplifiers whose desired gain characteristics are dependent on the hybrids used; either single or multiple frequency could be used with total gain and phase error determined by the isolation of the hybrids. Figure 23b shows the addition of filters which are made possible by multi-frequency operation. Figures 23c thru 23f have the advantage of using a single amplifier in conjunction with isolators which may be of the directional (d), frequency (c), or time (e) types. In figure 23f an amplifier is connected so that it looks like a negative impedance which compensates for the line loss. Since directional isolators and filters are quite temperature sensitive, the switching version appears to be the type offering the best performance.

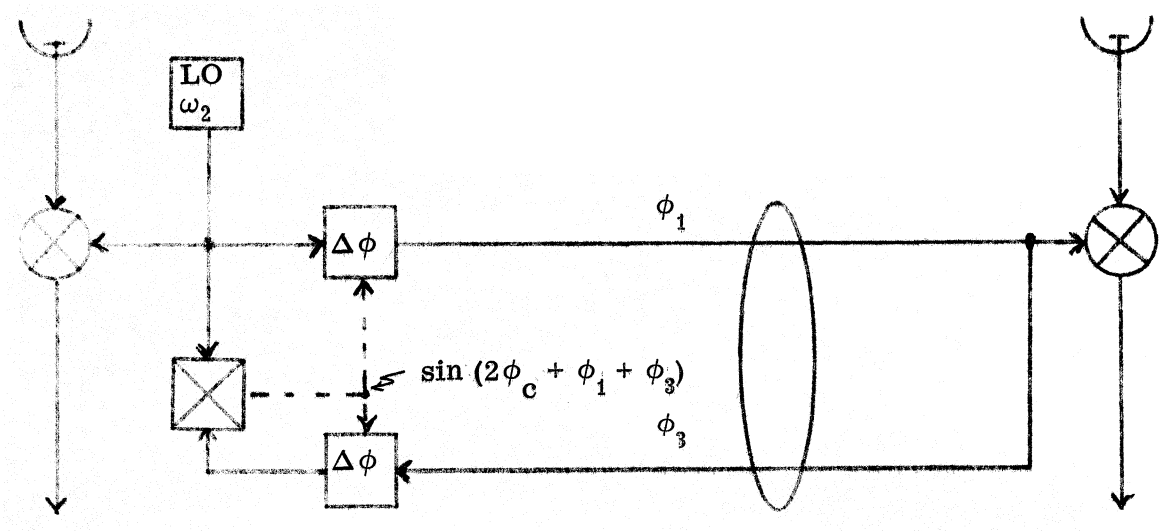


FIGURE 16

SINGLE SIDEBAND REFLECTED SYSTEM

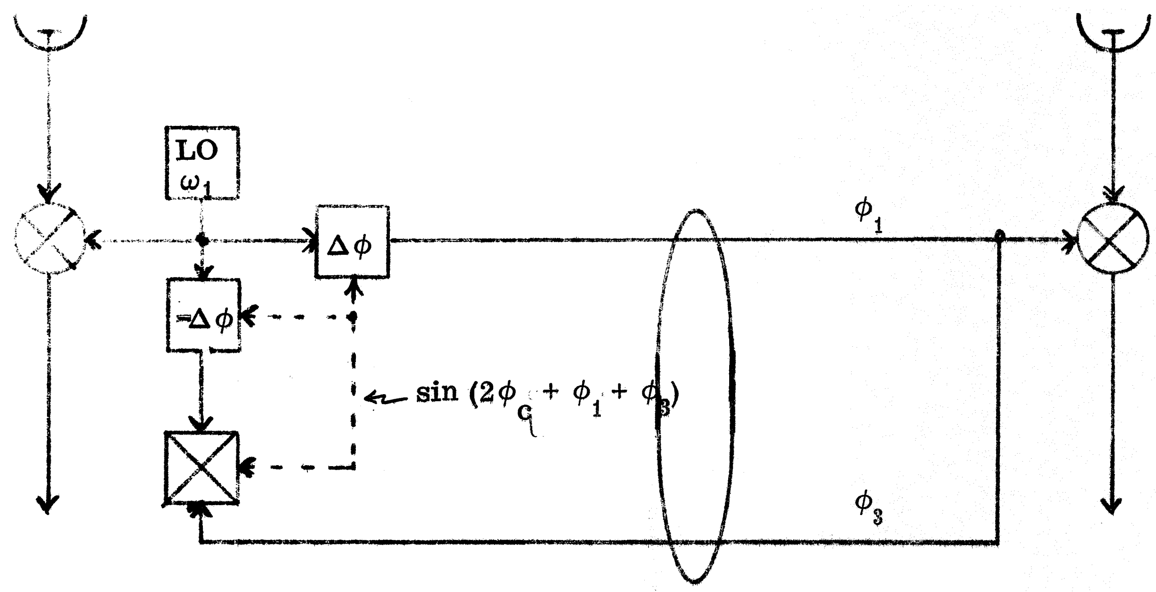


FIGURE 17

SINGLE SIDEBAND REFLECTED SYSTEM

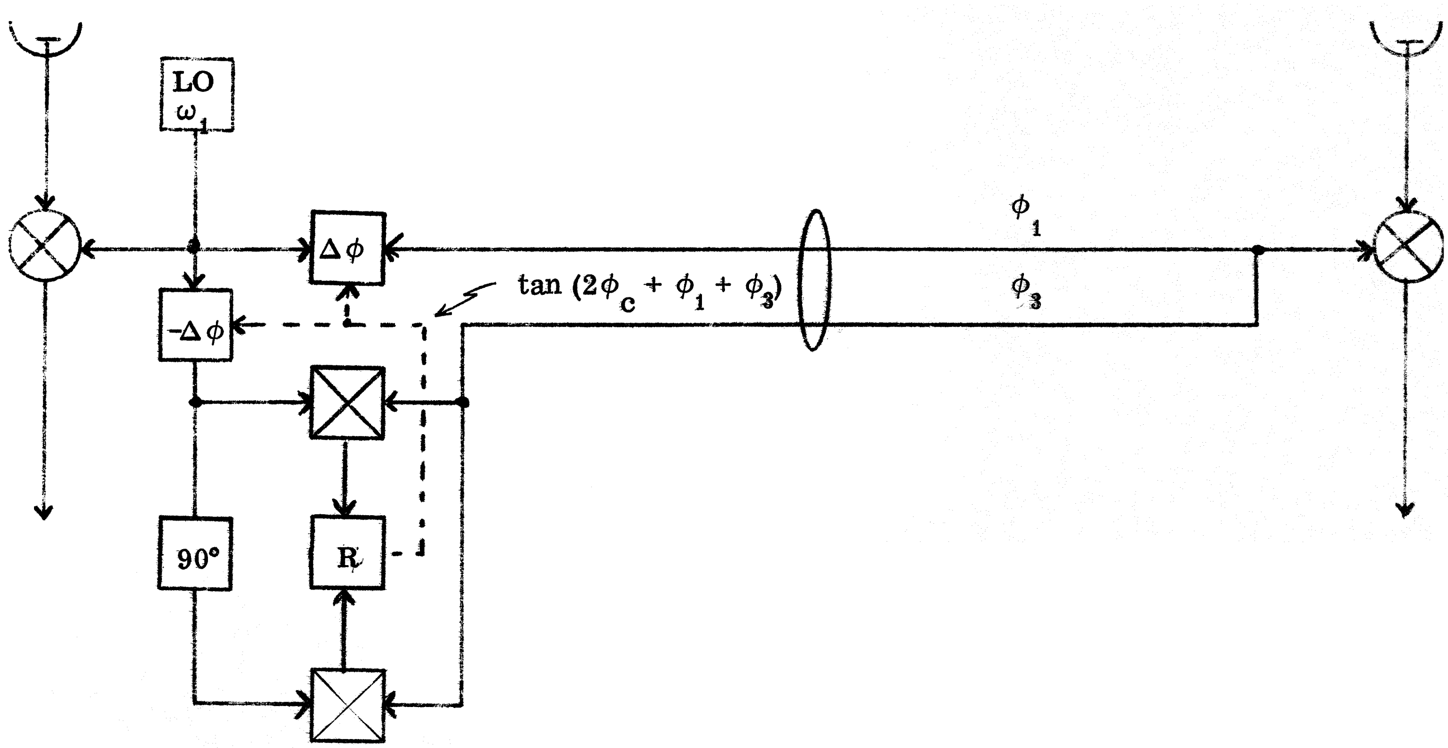


FIGURE 18

SINGLE SIDEBAND REFLECTED SYSTEM

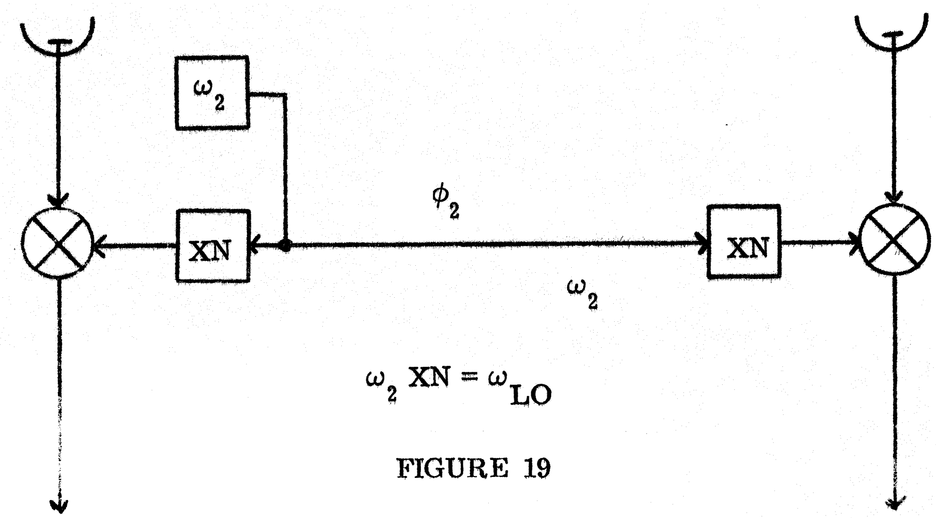


FIGURE 19

SEPARATE MULTIPLIER TYPE SYSTEM

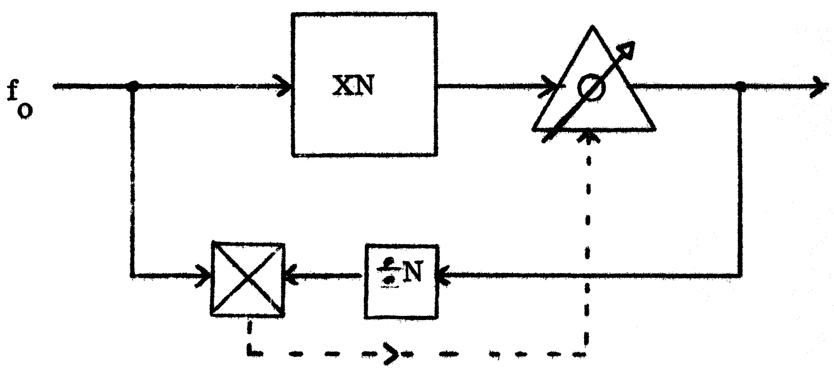


FIGURE 20

PHASE LOCKED MULTIPLIER

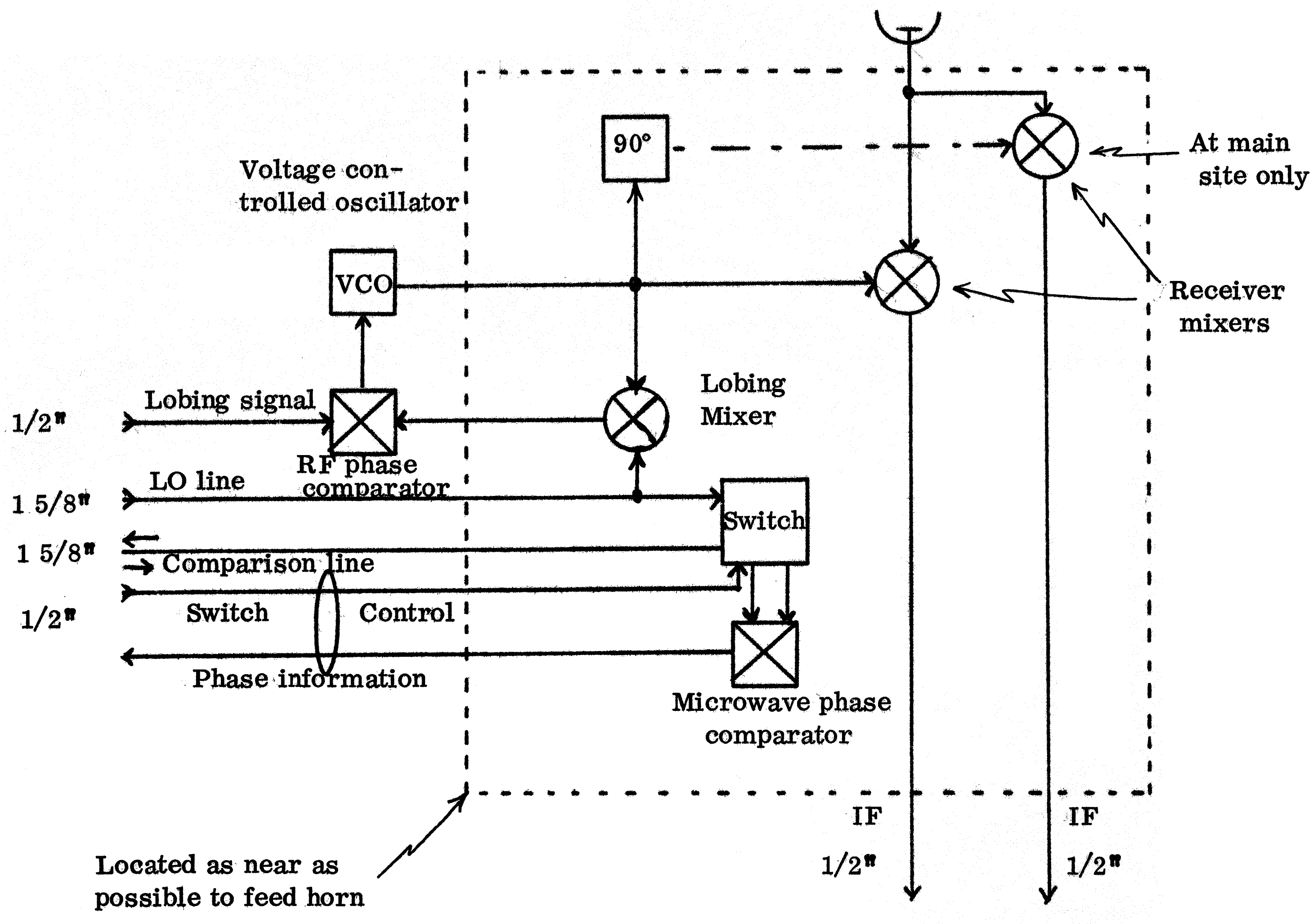


FIGURE 21

PLACEMENT OF SYSTEM COMPONENT PARTS AT EACH SITE WITH A SWITCHED, LOBE ROTATED SYSTEM

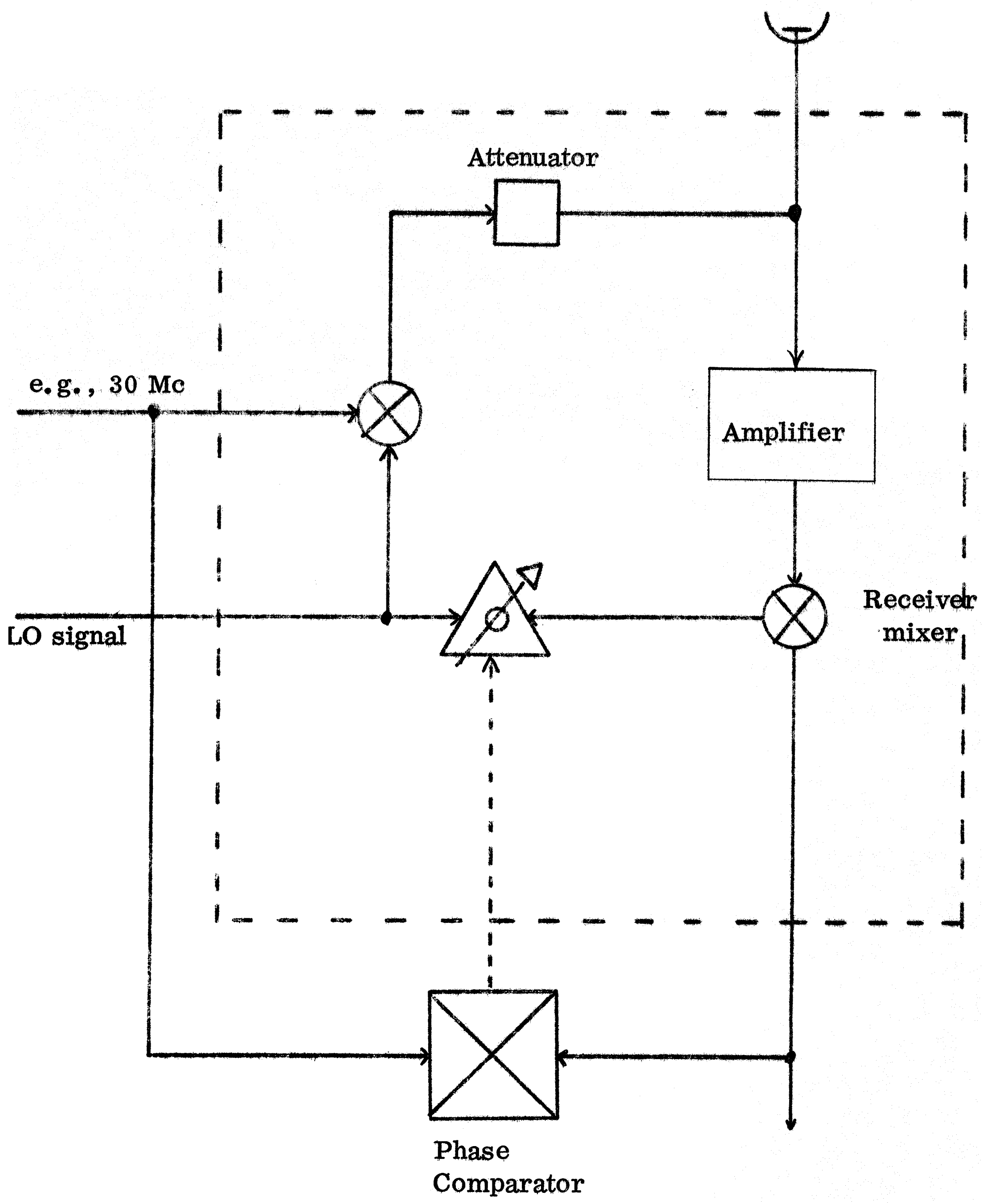


FIGURE 22

FRONT-END AMPLIFIER PHASE COMPENSATION

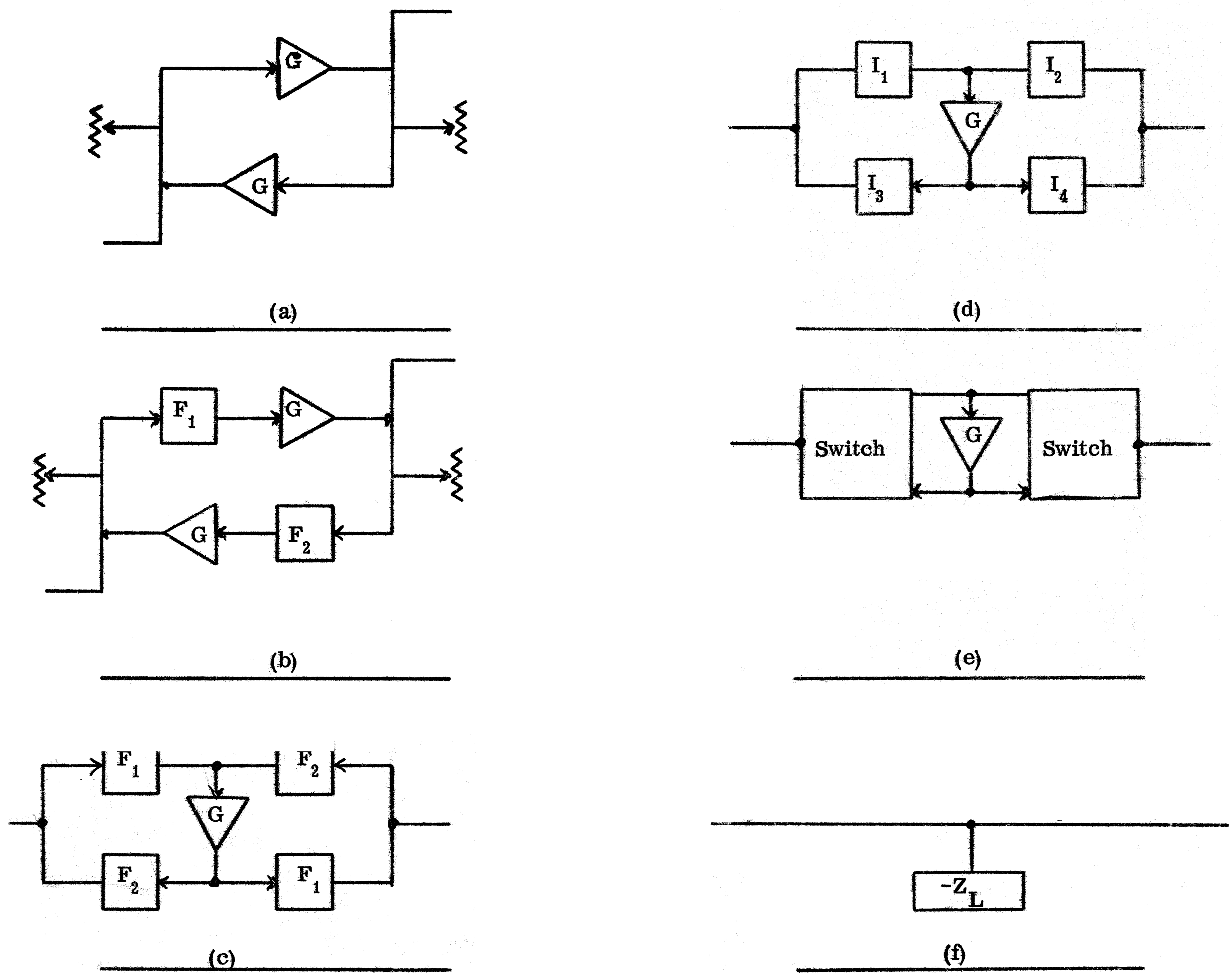


FIGURE 23
LINE AMPLIFIERS

V. Conclusions

The following points must be determined:

1. What are the limits of stability of a phase corrected amplifier?
2. What phase stability can be obtained with a low order multiplier?
3. What phase stability can be maintained by a high order multiplier?
4. What is the phase stability of microwave switching?

The frequency discrimination and directional discrimination schemes all suffer from errors introduced by repeater amplifiers and filters; therefore, if the answer to four above is acceptable, a switched system appears to have the greatest potential (see figures 9 and 21). If the answer to three is within the accuracy specified for the system, the high order multiplier system (see figure 19) would be preferable; if not, the design would be determined by points one, two and as previously mentioned, four.

In summary, the switched system will be pursued with the loop frequency being determined by considering the above points in conjunction with the ambiguity problem.

VI. References

[1] N. J. Keen, Electronics Division Internal Report No. 14.

[2] R. B. Read, Observations of the Owens Valley Radio Observatory, California Institute of Technology, 1963.