VLBA ELECTRONICS MEMO NO: 26

LOCAL OSCILLATOR LINK FOR PIE TOWN ANTENNA

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1.0 INTRODUCTION

A radio link system is considered here for connecting the VLBA antenna at Pie Town to the VLA Site to allow real-time correlation with the VLA. The aim is to design a frequency standard signal distribution system using a radio link which will have the ability to operate in a self-correcting mode (for path length changes) and meets the requirements of the VLBA local oscillator system. This report does not consider the link required for the return of IF data from Pie Town to the VLA.

2.0 SPECIFICATIONS ON VLBA LOCAL OSCILLATOR SYSTEM

The requirements of the VLBA local oscillator system are:

(1) At the maximum frequency of operation, 86 GHz, the short-term stability of the remote station oscillator should give at least 0.9 coherence (Hydrogen Maser Frequency Standard Specification - S. Weinreb, June 21, 1984). This corresponds to an rms phase noise of 26.3° at 86 GHz.

(2) Phase-stable signals at 5 MHz, 100 MHz, and 500 MHz are required for the local oscillator frequency synthesizer at the antenna. The primary local oscillator reference signal frequency being 500 MHz (Larry D'Addario VLBA Memo No. 303). At 500 MHz, specification (1) implies that the phase noise should not exceed 0.15° rms.

3.0 SOURCES OF PHASE NOISE

Primarily there are two factors that contribute phase noise to a frequency standard signal transmitted to a remote station on a radio link. These are:

(1) The available signal-to-noise ratio in the bandwidth of the receiver (i.e. remote station phase-locked loop bandwidth)

(2) The propagation path (i.e. troposphere) introduced random frequency modulation on any cw signal. This is due to the fact that a change in transit time of a signal produces a corresponding change in the phase of the received signal. Time changes in phase constitute changes in instantaneous frequency.

For frequency standards having inherent stability better than 10^{-12} propagation effects during transmission over a radio link can limit the quality of a frequency standard signal. Phase noise can be many times more than that contributed by receiver noise alone (Reference 1). To reduce phase instabilities from atmosphere, round-trip phase stabilization is needed.

3.1 Radio Link Scheme

The radio link is meant for transferring a phase-stable reference signal - derived from the hydrogen maser of the VLA - to the VLBA antenna to produce desired local oscillator frequencies. The feature of the system under consideration is it communicates in both directions. A signal at the reference frequency is sent and returned back to the master station. It measures variations in the bidirectional path delay caused by the atmosphere. Once the delay is measured it can provide an automatic correction to compensate changes. Figure 1 illustrates the basic scheme. The path delay is denoted by τ, and the reference signal frequency is ω and of zero phase. It is required to transmit this signal at ω and maintain the phase at the remote station.

This needs transmitting the phase as a leading angle so that as it passes through the link delay, it comes out with zero phase at the same frequency. At the remote station the signal is retransmitted starting with zero phase and is delayed by a negative angle equal to the return-link delay. If the path is bidirectional, the delays are the same for both directions. The transmitted signal and the received signal are compared in phase detectors and summed in an amplifier and applied as a correction to the VCXO. Any change in path length will cause the VCXO control voltage to change and re-establish the balance that is maintained at zero phase. The success of this scheme depends on the fact the path delay is the same in both directions. This is true if the same frequency signal is transmitted down and back. Generally a problem arises in transmitting and receiving the same-frequency signals simultaneously. A reflection of the transmitted signal from an antenna can be much stronger than the signal strength from a remote station. Thus discrimination of signals travelling in either direction becomes difficult. One solution to overcome this is a switching arrangement. The master transmitter is turned on and transmits for a short time (pulsed on). Then it is switched off and the associated receiver is turned on. This seems to be the most practical way of achieving the necessary isolation. This type of pulse mode operation was adapted at the VLA as well as at Green Bank for local oscillator transmission systems. In the scheme discussed here pulsed operation is planned with equal ON/OFF periods (total period ~20 msec). As the scheme ,verify assumes that the path is bidirectional, any multipath propagation due to either reflections or diffraction effects is also bilateral.

3.2 Green Bank Local Oscillator Link

At Green Bank, a phase-stable local oscillator link is in operation at 17 GHz (Interferometer Microwave Link - Jim Coe). It is a closed-loop system. With a view to adopt this scheme the following analysis is carried out. The principle of operation of this scheme is shown in Fig. 2. Signals at the indicated locations on Fig. 3 are given here along with their radian frequency and phase for simplicity. In the expression given below c is propagation velocity of electromagnetic waves in the medium.

A Signal transmitted from control station ω_1 ϕ_1

B ω_1 $(\phi_1 - \frac{\omega_1 L}{c})$

C ω_2 ϕ_2

D Signals A and C are $\omega_2 = (\omega_1 - \omega_m)$

Summed: (i) $(\omega_i + \omega_2)$ $(\phi_1 - \frac{\omega_1 L}{c} + \phi_2)$

(ii) $(3\omega_2 - \omega_1)$ $(3\phi_2 - \phi_1 + \frac{\omega_1 L}{c})$

E $2\omega_2$ $2\phi_2$

F (i) Taking difference of: D(i) and E $(\omega_i - \omega_2)$ $(\phi_1 - \frac{\omega_1 L}{c} - \phi_2)$

(ii) D(ii) and E $(\omega_i - \omega_2)$ ϕ_2

G Received low-frequency reference at remote station ω_m $(\phi_m - \frac{\omega_m \ell}{c})$

Phase detection and closing the loop yields under phase-lock condition $\omega_2 = (\omega_1 - \omega_m)$

The presence of signal F(ii) shifts the phase of the local oscillator signal in the loop to change to ϕ_2'

$\phi_2' = (\phi_2 - \phi_c)$ where ϕ_2 corresponds to the phase of the local oscillator in the absence of the signal at frequency $(3\omega_2 - \omega_1)$.

$$\phi_2 = (\phi_1 - \frac{\omega_1 L}{c} - \phi_m + \frac{\omega_m \ell}{c})$$

H Signal transmitted from remote station $\omega_2 \quad \phi_2'$

J Signal received at control station $\omega_2 \quad (\phi_2' - \frac{\omega_2 \ell}{c})$

K $\omega_3 \quad \phi_3$

L $(\omega_2 - \omega_3) \quad (\phi_2' - \frac{\omega_2 \ell}{c} - \phi_3)$

M $\omega_m \quad \phi_m$

under phase-locked condition of PLL-2

$(\omega_2 - \omega_3) = \omega_m$

$(\omega_1 - \omega_3) = 2\omega_m$

$$\phi_3 = (\phi_2' - \frac{\omega_2 \ell}{c} - \phi_m)$$

$$\phi_3 = (\phi_R - \phi_1) = \phi_1 - \frac{2\omega_1 L}{c} + \frac{2\omega_m L}{c} - 2\phi_m - \phi_e$$

$$2\phi_1 = \phi_R + \frac{2\omega_1 L}{c} - \frac{2\omega_m L}{c} + 2\phi_m + \phi_e$$

Remote station local oscillator signal is

$2\omega_2 \quad 2\phi_2' = \omega_R \quad 2\phi_2'$

$2\phi_2' = (2\phi_2 - \phi_e)$

$2\phi_2 = (\phi_R - \phi_e)$

It is seen that the phase error ϕ_e at the remote station arises due to the 3rd harmonic of f_2 mixing with f_1 producing a signal at frequency $(3f_2-f_1)$ which when combined with $2f_1$ gives an image of the desired signal. For commercially available double-balanced mixers the signal level of $(3f_2-f_1)$ is about 10 to 13 dB below that of the desired signal. This produces a phase error of about 12 to 18° for the remote station local oscillator reference signal.

The scheme requires an offset-frequency signal to be transmitted to the remote station phase locked loops, for discrimination of signals received and transmitted.

A possible alternative to the above scheme is to monitor path-length changes using a round-trip phase measurement scheme similar to the one used at the VLA for local oscillator signal distribution. However, to reduce the phase noise from atmospheric variations, real time adjustments can be applied to the remote station oscillator using the scheme suggested in Fig. 1. In the system considered here signals at two frequencies with separation of 500 MHz are transmitted to the remote station where they are mixed to give a signal at 500 MHz. A highly-stable crystal oscillator at 5 MHz with frequency amplifiers is phase-locked to this reference signal. The phase locked signal is then returned to the control station where the transmitted 500 MHz signal and received 500 MHz signal are compared in phase detectors against a reference 500 MHz obtained from hydrogen maser. The two outputs are combined to produce an error signal that controls a VCXO. This keeps the phase of the transmitted 500 MHz signal always at leading angle which makes phase of the remote station 500 MHz reference signal the same as that of the reference signal phase derived from the hydrogen maser frequency standard at master station.

The exact frequencies of operation and specific hardware implementation depends upon assigned frequencies. It is likely assignments at 7235 MHz, 7255 MHz, 7725 MHz, and 7750 MHz will be available with about 10 MHz bandwidth around each carrier for operating the radio link. A possible hardware implementation is shown in Figs. 4 and 5 for a link at 7.5 GHz.

4.0 SIGNAL LEVEL CALCULATIONS

Signal level calculations for a link are given at 3 different frequencies; 1.8 GHz, 7.5 GHz and 17 GHz. Table 1 gives path losses for a radio link via two different paths (Figs. 6 and 7) - (1) VLA Site - Davenport Peak - Pie Town, (2) VLA Site - Mangas Peak - Pie Town. It is seen that a link via Davenport Peak has 8 dB less loss compared to a link via Mangas Peak. Hence, a repeater station at Davenport Peak is considered here. In the signal-to-noise calculations given in Table 2 a passive repeater with flat reflectors is used besides the following:

(1) Parabolic antennas (2m dia.) at the VLA site and Pie Town

(2) Flat reflector for passive repeater 2m x 4m size

(3) System temperature 300°k (antenna temp 150°k + receiver temp 150°k)

(4) Receiver noise bandwidth 10 Hz

(5) Atmospheric absorption at 7 GHz 0.005 dB/Km
at 17 GHz 0.1 dB/Km

(6) Fade margin 20 dB at 7.5 GHz, 25 dB at 17 GHz.

Without actual measurements on path, estimation of fade margins is difficult. Jim Coe's measurements at 17 GHz over a 33 km path at Green Bank reveal that the signal is within ±6 dB for 99% of the time. We have a longer radio path than that at Green Bank. As troposphere at New Mexico can be considerably different from that at Green Bank extrapolating Green Bank's measurements may not be very meaningful. One significant difference is that atmospheric inversion layers can form in the desert/mountain environment. Based on Rayleigh fading, a 20 dB fade is likely for 1% of the time and a 30 dB for 0.1% of the time. Rain attenuation is not included separately as rain breaks up the atmosphere with stratified layers which are responsible for multipath fading.

It is seen from Table 2 that for moderate transmitter powers (+30 dBm) a signal-to-noise ratio of 65 dB is achievable. Additional improvements can be obtained by increased antenna sizes and transmitter power outputs. From the specifications on the local oscillator phase noise a minimum signal-to-noise of 49 dB is required for an rms phase noise of 0.15° at 500 MHz in a receiver bandwidth of 10 Hz. A signal-to-noise in excess of 60 dB indicates that the phase jitter can be much less than 0.05° rms which corresponds to a fractional-frequency stability of 3 parts in 10^{-12} ($\Delta\phi = 360\ (\frac{\Delta f}{f}) f\ T$; $f = 500$ MHz; $T =$ o.1 sec; $\Delta\phi = 0.05°$ rms).

In reference 1 measured fractional frequency stability for a 9 GHz signal transmitted over a 50 km path as a function of observing time were presented. This indicates that the fractional frequency stability can be represented by $(\frac{\Delta f}{f}) = 5 \times 10^{-12} \bullet T^{-1}$ for $10^{-2} < T < 10^{+1}$.

Based on this one can estimate expected phase jitter on a reference frequency signal obtained as a difference between two microwave carriers. The phase jitter at 500 MHz corresponds to about 0.9° rms over periods of 1/10 second. This is phase noise on the reference signal input to the phase-locked loop. It can only be reduced by decreasing the receiver bandwidth or making use of a scheme to cancel out phase noise. One of the ways to do this is shown in Fig. 1. where phase noise tracked by the receiver at the remote station is subtracted out from the transmitted signal using a feed back loop.

5.0 DIFFRACTION EFFECTS

From the location map of the VLA site, Davenport Peak and Pie Town areas it is seen that ridges of varying heights typically 8000 to 8500 feet run across the line-of-sight between the VLA and Pie Town. Thus there is a possibility for a signal transmitted through a side lobe of an antenna being received through a side lobe of a receiving antenna directly. Because of ridges, diffraction loss takes place besides normal free-space loss. In reality, diffraction effects are more complicated by the actual obstacle shapes, atmosphere and distances. For calculation of diffraction loss knife-edge diffraction formulas are often useful. Using this formulation an obstruction loss of 33 dB over free-space loss has been estimated. Thus a signal of ~55 dB below that of the signal through main lobe can arrive at the receiver. Polarization change of the received signal at Davenport Peak before transmission will be helpful to overcome spurious signals arising from radiation through sidelobes.

For implementing polarization change over at the repeater station we need to use back-to-back mounted parabolic antennas with a waveguide tracking the effects of polarization change. This seems to be very desirable and is convenient to mount on the existing microwave tower of MCI at Davenport Peak. For a flat reflector repeater system we need a close-coupled double passive arrangement similar to the one shown in Fig. 8. Since Pie Town and the VLA site are almost in line-of-sight with each other. Mounting of such a close-spaced double-passive flat reflector of ~2m x 6m size is not feasible on the MCI tower. Hence using back-to-back coupled, 2m or 3m diameter paraboloids seems to be a good practical approach. If 3m diameter paraboloids are used for antennas of the link (including for the repeater) an additional 4 dB improvement in signal-to-noise ratio occurs.

The other factors that contribute to phase noise are (i) mechanical vibrations of link antennas (ii) differential phase characteristics of automatic gain control amplifiers that are required to keep signal level at the input to the loop constant in the event of fading. Structural vibrations of antennas due to winds essentially cause (i) amplitude modulation noise and (ii) phase changes. Any phase transient due to wind bursts will be tracked out and slow random vibrations that cause linear movement of antennas produce phase noise equivalent to path changes. A receiver having a noise bandwidth ~10 Hz should be able to track these noises. Amplitude noise is however taken care by AGC amplifiers. When received signal levels vary (as is the case during a fade) the combined output power at frequencies f_1 and f_2 is used to control gain so that output power is constant. The phase introduced at f_1 can be different from that at f_2 for the amplifiers at the remote and control stations which introduce phase errors. Hence over a bandwidth of 500 MHz the amplifier phases should track to 0.01° for the AGC amplifiers at the control and remote stations.

From the above discussion, it can be summarized that system limitations can arise from two different sources:

(1) Receiver system noise

(2) Path delay fluctuations.

Although available data is sparse the most severe being the path through a turbulent atmosphere that causes greater phase noise on the reference transmitted to a remote station. A round-trip phase stabilization with closed loop compensation can reduce FM noise on a reference signal transmitted from a frequency standard over a radio link.

A budgetary estimate of the cost of the link is included.

REFERENCES

[1] M.C. Thompson, "Effects of Troposphere on the Propagation Time of Microwave Signals", Radio Science, Vol. 10, No.7, pages 727-733, July, 1975.

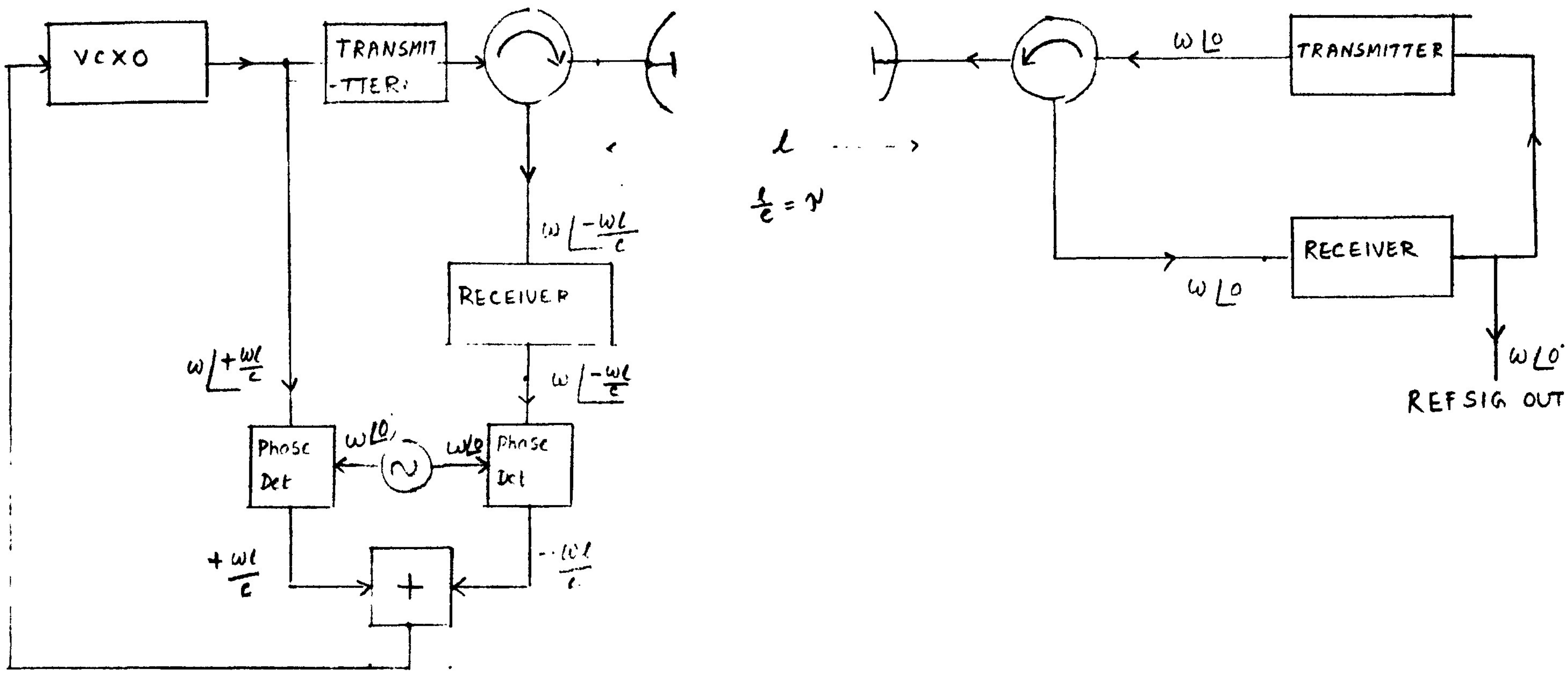


FIGURE. 1. A scheme for path length compensation.

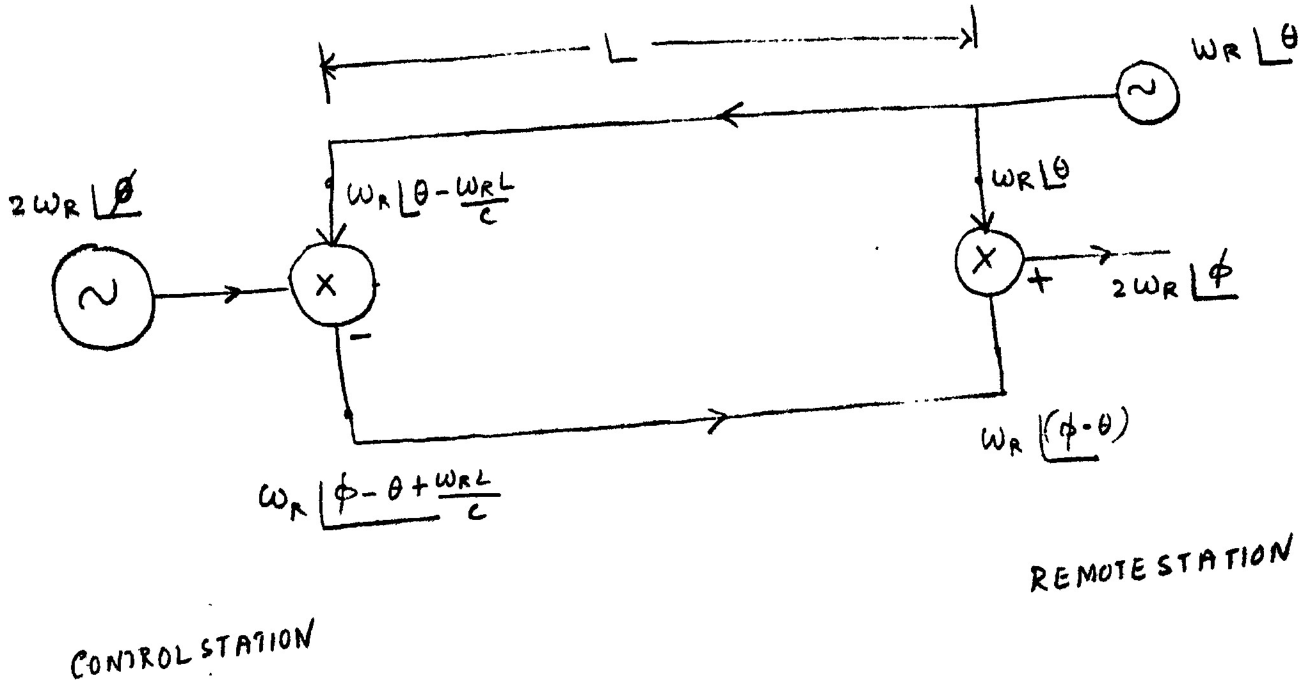
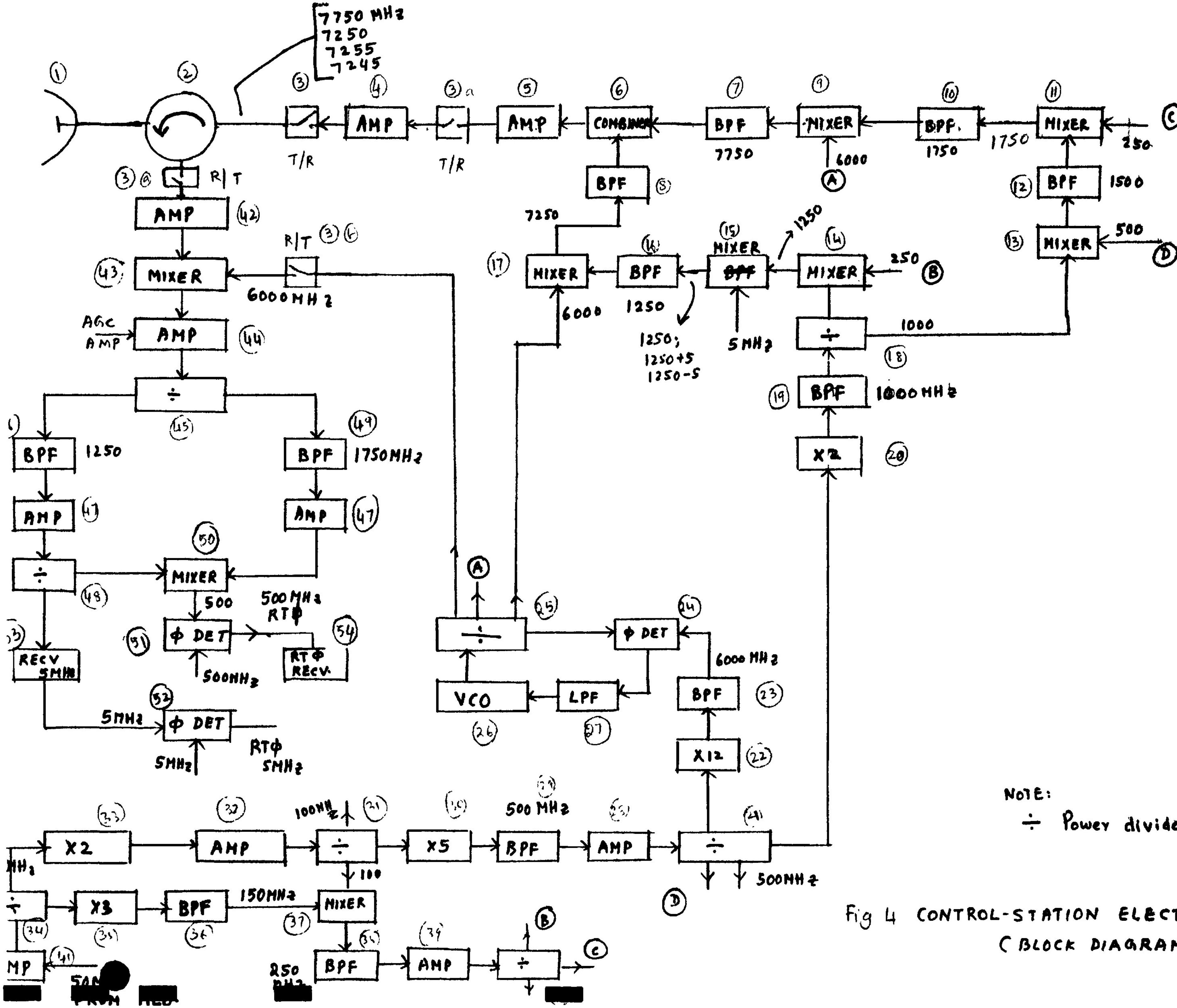
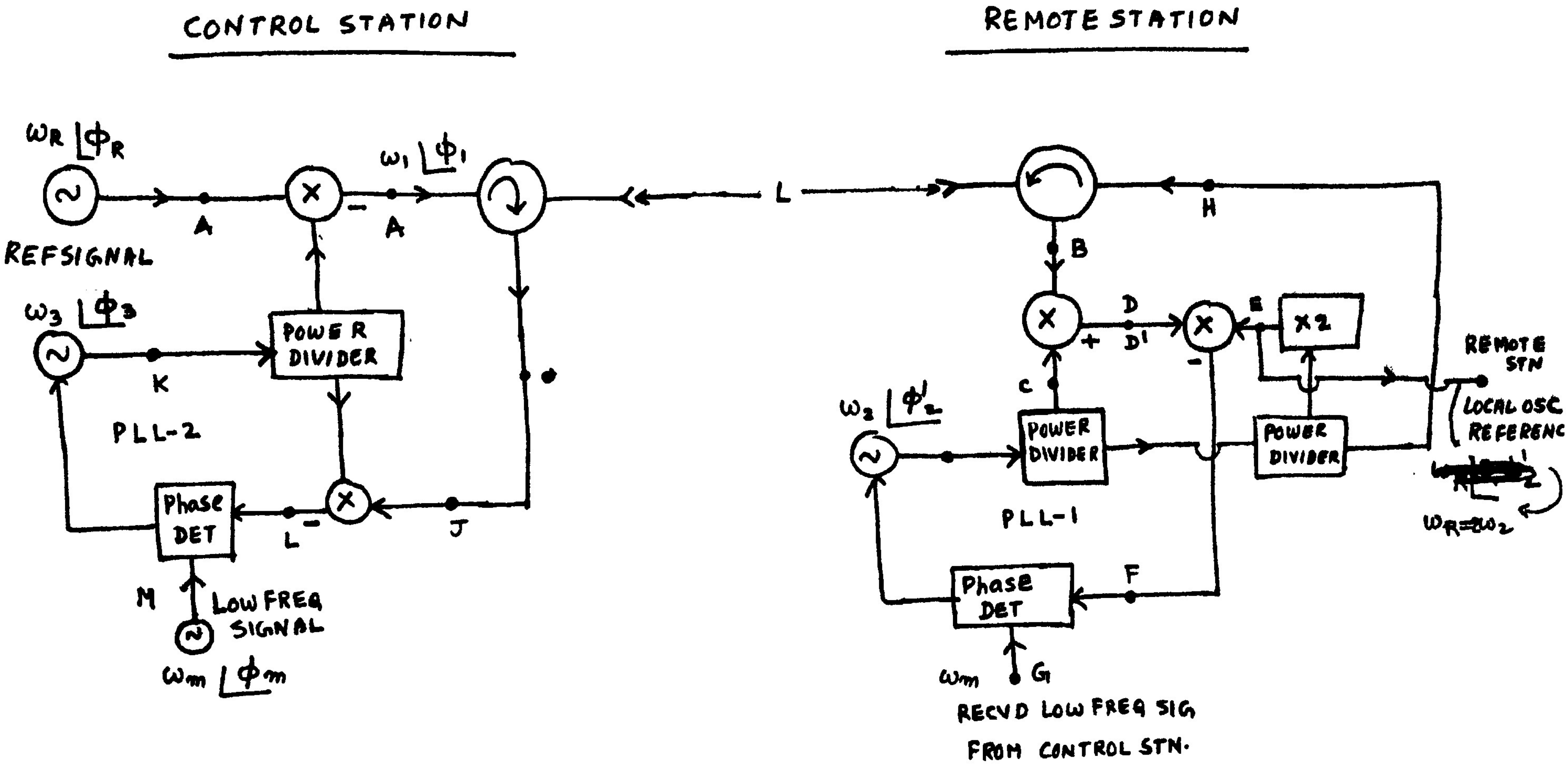


Figure 2 Principle of operation of Green Bank Local Oscillator System



NOTE:
÷ Power divider.

Fig 4 CONTROL-STATION ELECTRONICS (BLOCK DIAGRAM)



FIG·3 A closed-Loop path-Correcting System.

(This Scheme ~~was ad~~ is used at GREEN BANK.)

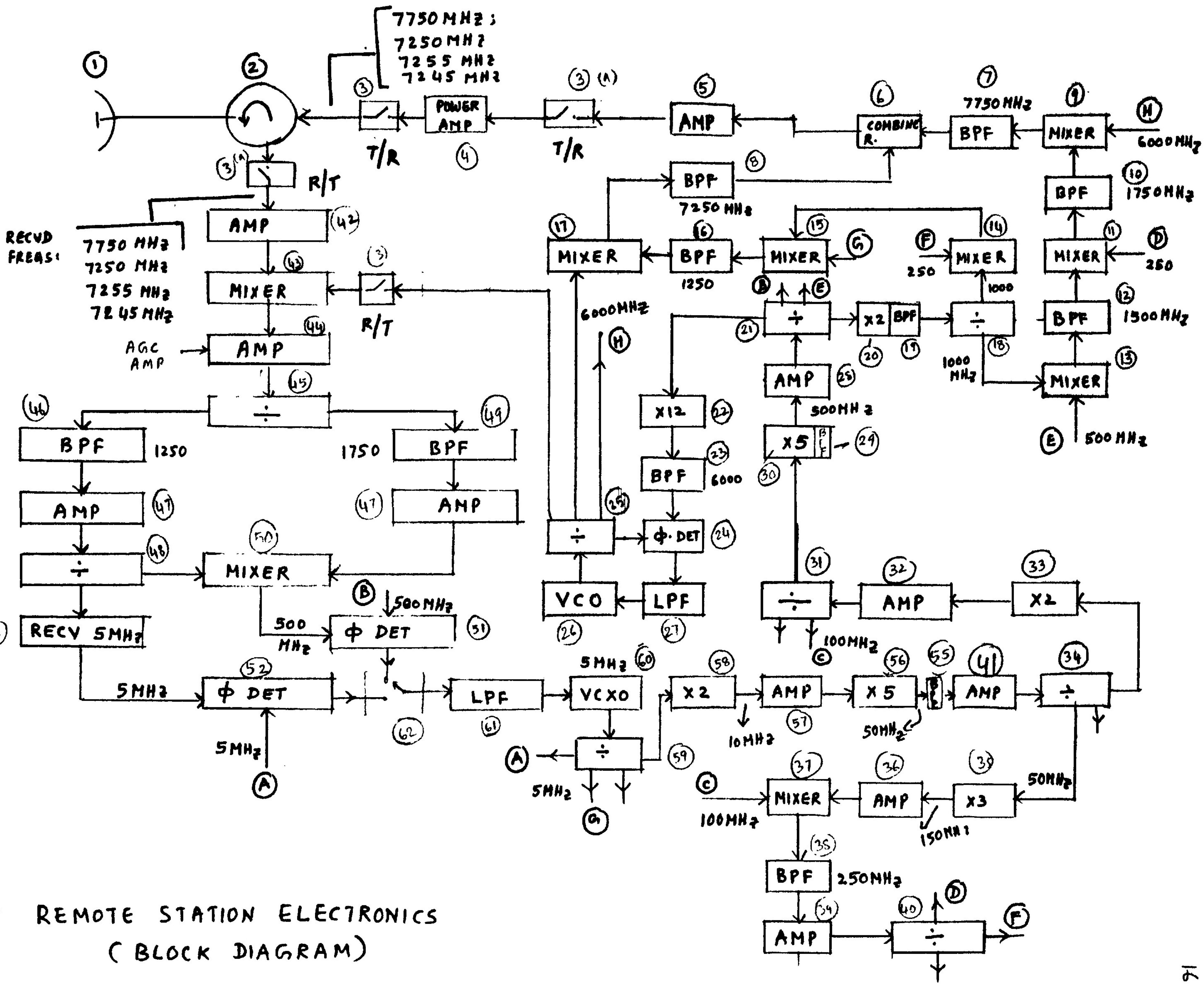
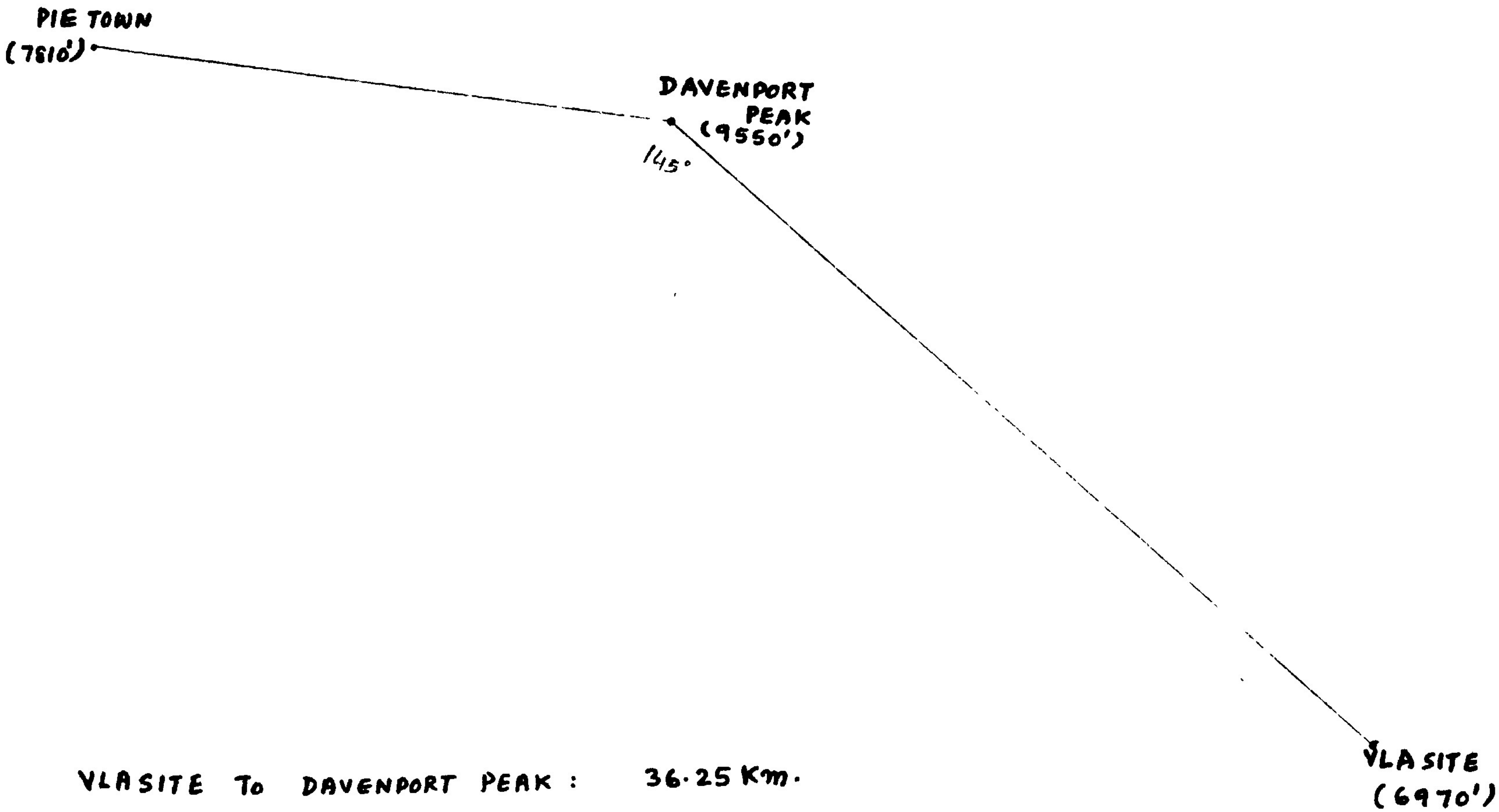


FIG: 5 REMOTE STATION ELECTRONICS
(BLOCK DIAGRAM)

Figure 6 SITE LOCATION (VLA: DAVENPORT PEAK; PIETOWN)

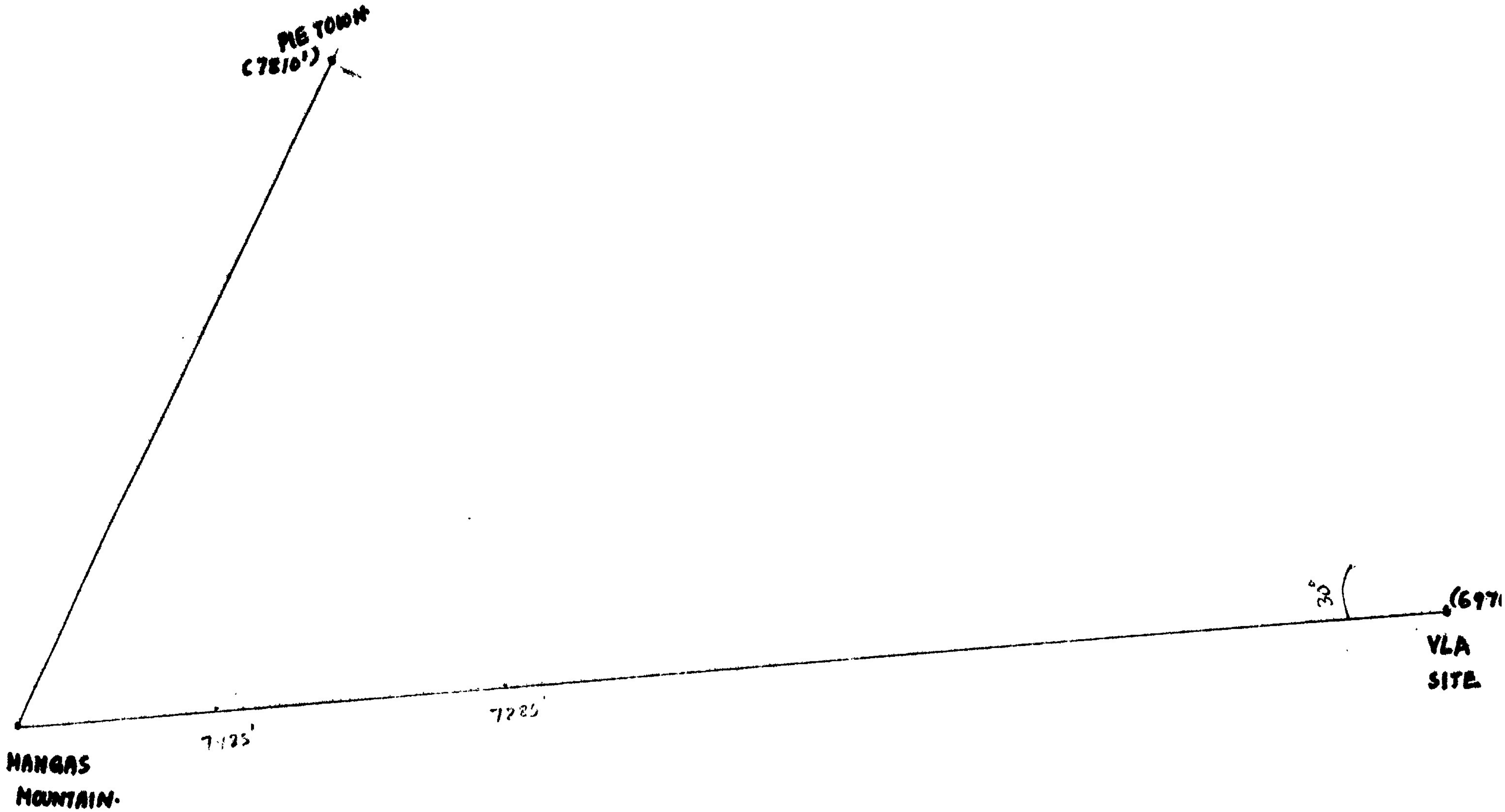
(1cm → 2.5 km on map)



VLASITE TO DAVENPORT PEAK : 36.25 Km.

DAVENPORT PEAK TO PIE TOWN : 21.25 Km.

[redacted] · [redacted] [redacted]E L[redacted]TI[redacted] ([redacted] : [redacted]GA[redacted]; [redacted]TOU[redacted]



VLASITE to MANGAS Mt. : 62.5 Km (38.83 mi)

MANGAS Mt to PIE TOWN : 32 Km (19.88 mi)

TABLE 1

FREQUENCY (GHz)	FREE SPACE LOSS (dB) Pie Town to Davenport	Davenport to VLA Site	TOTAL LOSS dB	FREE SPACE LOSS (dB) Pie Town to Mangas	Mangas to VLA Site	TOTAL LOSS (dB)
1.8	124	129	253	128	133	261
7.5	137	141	278	140	146	286
17	144	148	292	147	153	300

Free-space-loss = 92.4 + 20 log f (GHz) + 20 log d (km) (dB)

TABLE 2

LINK VIA DAVENPORT PEAK, PASSIVE REPEATER

DESCRIPTION	1800 MHz	7500 MHz	17,000 MHz
Free Space Loss	253 dB	278 dB	292
Close Coupling Loss (Passives)	3	1.2	1
Component Loss	6	6	6
Fade Margin		20	25
Atmospheric Absorption Loss		0.3	6
Total System Loss dB	262 dB	305.5 dB	330 dB
Transmitting Antenna Gain (2m dia)	28 dB	41	48
Receiving Antenna Gain (2m dia)	28	41	48
Net Passive Repeater Gain (2mx4m)	70	95	109
Total Gain	126 dB	177 dB	205 dB
Transmitter Power Output	+30 dBm	+30 dBm	+30 dBm
Received Signal Power Level	-106 dBm	-98.5 dBm	-95 dBm
Receiver Noise Level $T_s = 300°K$	-164 dBm/10 Hz	-164 dBm/10 Hz	-164 dBm/10 Hz
Signal-to-Noise (dB)	58 dB	65.5 dB	69 dB

TABLE 3

DESCRIPTION	LOSS/GAIN (dB)
Free Space Loss	145 dB
Component Loss	6
Diffraction Effect (Knife-edge loss)	33
Total Loss	184 dB
Transmitting Antenna Gain	0
Receiving Antenna Gain	0
Transmitter Power	+30 dBm
Received Signal Level Due to Side Lobes & Diffraction Effects	-154 dBm
Desired Signal Power/Interference Signal Power	55.5 dB

TABLE 4

VARIATION IN ANGLE OF ARRIVAL OF WAVEFRONT

LINK PATH	ANGLE OF ARRIVAL
Pie Town - Davenport	±0.07°
Davenport - VLA Site	±0.13°
Pie Town - Mangas	±0.1°
Mangas - VLA Site	±0.21°

Figure 8

VLA-PIE TOWN LOCAL OSCILLATOR LINK
(With Passive Repeater)

ITEM	DESCRIPTION	ESTIMATED COST $	QUANTITY	TOTAL COST $
1	10 foot Parabolic reflectors & feed surface tolerance ~0.015" rms feed bandwidth 800 MHz VSWR <1.1	7,000	4	28,000
2	3-port circulator; CW power rating ~15 watts freq 7 to 8 GHz, Isolation 40 dB VSWR <1.1 Insertion loss <0.3 dB	300	2	600
3	Transmit receive switch ON/OFF operating freq 7 GHz to 8 GHz VSWR <1.1 Isolation ~50 dB			
(a)	Insertion loss ~0.5 dB, CW power handling capability ~15 watts	1,000	2	2,000
(b)	Insertion loss ~0.2 dB, CW power handling capability ~2 watts	500	4	2,000
(c)	Insertion loss ~0.2 to 0.3 dB; operating freq 6 GHz Isolation ~30 dB P_c ~ + 20 dBm	300	2	600
4	Solid-state power amplifier P_o ~10 watts. Pin ~ +30 dBm; BW ~800 MHz at 7.5 GHz Unconditionally stable, input/output 50 ohms.	800	2	1,600
5	Solid-state power amplifier P_o ~1 watt P_{in} 1mw freq 7 to 8 GHz VSWR ~1.1 Unconditionally stable	500	2	1,000
6	Power combiner Isolation ~30 dB freq 7 to 8 GHz VSWR <1.1	300	2	600
7	Band Pass filter f_o = 7750 MHz, BW_{3dB} ~100 MHz VSWR <1.1 Insertion loss ≤0.3 dB	500	2	1,000
8	Band Pass filter f_o = 7250 MHz, BW_{3dB} ~100 MHz VSWR <1.1 Insertion loss ≤0.3 dB	500	2	1,000

ITEM	DESCRIPTION	ESTIMATED COST	QUANTITY	TOTAL COST
9	Double-balanced Mixer; LO 6 GHz IF 7.75 GHz RF 1.75 GHz	600	2	1,200
10	Band Pass filter f_o = 1750 MHz, BW_{3dB} 150 MHz	200	2	400
11	Double-balanced mixer; LO 250 MHz; RF 1500 IF 1750 MHz	200	2	400
12	Band Pass filter f_o 1500 MHz BW_{3dB} ~150 MHz	200	2	400
13	Double-balanced mixer; LO 500 MHz; RF 1000 MHz IF 1500 MHz	300	2	600
14	Double-balanced mixer; LO 250 MHz; RF 1000 MHz IF 1250 MHz	300	2	600
15	Double-balanced mixer; LO 5 MHz; RF 1250 MHz IF 1250 MHz ± 5 MHz	250	2	500
16	BPF f_o 1250 MHz BW ~100 MHz	200	2	400
17	Mixer LO 6000, RF 1250 IF 7250 MHz	600	2	1,200
18	Power divider: Two-way freq ~1000 MHz Isolation ~30 dB	100	2	200
19	Bandpass filter 1000 MHz 10% bandwidth	250	2	500
20	Frequency doubler P_o ~+10 dBm f_o = 1000 MHz f_{in} = 500 MHz	150	2	300
21	Power divider 4 way f_o = 500 MHz	150	2	300
22	Frequency multiplier x12 f_o = 6000 MHz f_{in} = 500 MHz	4,500	2	9,000
23	Bandpass filter f_o ~6000 MHz BW ~5%	400	2	800

ITEM	DESCRIPTION	ESTIMATED COST	QUANTITY	TOTAL COST
24	Phase detector (i.e. DBM) @ 6000 MHz + 7 dBm inputs	300	2	600
25	Power divider 4-way f_o ~6000 MHz	300	2	600
26	Voltage controlled oscillator f_o ~6000 MHz P_o ~100 mw	1,500	2	3,000
27	Phase lock loop board, control circuitry etc.	150	2	300
28	Power amplifier; freq 500 MHz P_{in} 0 dBm P_o ~+ 30 dBm	300	2	600
29	Bandpass filter f_o 500 MHz BW_{3dB} ~10%	150	2	300
30	Frequency multiplier; f_{in} = 100 MHz; f_o = 500 MHz P_o ~+10 dBm	2,000	2	4,000
31	Power divider @ 100 MHz 3-way	150	2	300
32	100 MHz Power amplifier P_o ~+ 20 dBm	300	2	600
33	Frequency doubler f_{in} = 50 MHz f_{out} = 100 MHz P_{out} ~+13 dBm	150	2	300
34	Power divider 50 MHz	50	2	100
35	Frequency tripler f_{in} = 50 MHz f_o = 150 MHz P_{out} ~+13 dBm	250	2	500
36	Bandpass filter f_o 150 MHz BW_{3dB} ~10%	200	2	400
37	Double balanced mixer LO 100 MHz, RF 150 MHz IF 250 MHz	100	2	200
38	Bandpass filter f_o = 250 MHz BW_{3dB} 10%	200	2	400

ITEM	DESCRIPTION	ESTIMATED COST	QUANTITY	TOTAL COST
39	Amplifier; f_o 250 MHz P_{out} ~+20 dBm P_{in} ~-10 dBm	200	2	400
40	Power divider 3-way @ 250 MHz	150	2	300
41	50 MHz Amplifier P_{out} +13 dBm P_{in} = 0 dBm	200	1	200
42	Low Noise Amplifier ~800 MHz BW T_R ~100°K or less f_o ~7500 MHz	4,000	2	8,000
43	Mixer LO 6 GHz @ Power ~+7 dBm RF 7 to 8 GHz IF 1 to 2 GHz	500	2	1,000
44	Amplifier 1 to 2 GHz Gain ~30 dB	700	2	1,400
45	Power Divider 1 to 2 GHz Two-way	300	2	600
46	Same as 16	200	2	400
47	Amplifier 1 to 2 GHz Gain ~30 dB	700	2	1,400
48	Power divider 1 to 2 GHz Two-way	300	2	600
49	Same as item 10	200	2	400
50	Mixer RF & LO 1250 & 1750 MHz IF 500 MHz	250	2	500
51	Phase Detector 500 MHz @ +7 dBm inputs	100	2	200
52	5 MHz Phase detector	50	2	100
53	5 MHz Receiver	150	2	300
54	Round-trip phase measurement receiver	300	1	300
55	Bandpass filter 50 MHz	100	1	100

ITEM	DESCRIPTION	ESTIMATED COST	QUANTITY	TOTAL COST
56	Frequency multiplier x5 10 MHz to 50 MHz	100	1	100
57	Amp 10 MHz	100	1	100
58	Frequency doubler f_{in} 5 MHz f_{out} 10 MHz P_o ~+10 dBm	100	1	100
59	Power divider 4-way 10 MHz	50	1	50
60	5 MHz VCXO	1,000	1	1,000
61 & 62	Phase Lock Loop circuitry and Phase detectors etc.	250	1	250
63	Connectors			2,000
64	Waveguide lengths & cables			2,500
65	Waveguide twists, attenuators, phase shifters, magic T's			3,000
66	Power supplies			3,000
67	Miscellaneous components PC Boards, Heat Sinks, etc. + any extra amplifiers <u>or</u> OSC, Feed Thru's, filters			5,000
	Estimated Cost:			$100,700
	15% for contingencies			15,105
	Estimated Total Cost			$115,805

Man Power estimate ~

(1) Engineering	1½ years
(2) Technician	1½ years
(3) Draftsman	½ year
(4) Workshop	½ year