AN RF SYSTEM FOR MILLIMETER WAVE PROPAGATION EXPERIMENTS

by

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SECTION 1

INTRODUCTION

1.1 Contents of the Section

Path length, expected range of data, RF system functions, and RF system controls are all discussed in order to better define the receiver and transmitter specifications.

1.2 Path Length and Expected Range of Data

Rain-induced depolarization and attenuation are phenomena that can only be observed over a finite propagation distance. The distance over which they should be observed is dependent primarily upon the expected rainfall rate, the frequency, and the available RF components. As an example, suppose one wishes to measure cross-polarization levels of -50.0 dB. (Cross-polarization is defined as the ratio of the cross-polarized channel received power to the co-polarized channel received power.) If the RF system has a polarization isolation of 45.0 dB, the -50.0 dB level cannot be observed. The point is that although path length is the first parameter that should be established in the design of a millimeter wave propagation system, it should not be established without some thought given to the RF components needed to measure the phenomena in question at that path length.

For attenuation and depolarization experiments, the procedure for determining path length is straight forward once the operating frequency, lower rainfall rate, and upper rainfall rate are known. The normal boundaries on rainfall rate should be determined by local climatological history.

A lower limit on the path length is found by calculating the minimum distance at which the effect can be observed and measured. Thomas[1] provides curves of attenuation per kilometer vs frequency for varying rainfall rates for those interested in attenuation only. He also explains the differential attenuation method for predicting cross-polarization levels between two orthogonal linearly polarized channels. This is very useful in determining the expected signal levels that must be detected and measured. Recent works by Watson[2] and Wiley[3] also provide similar but improved information.

An upper limit on path length is found by considering two basic questions. First, will the rain remain fairly constant over the path; second, will erroneous data result from ground reflections? Local climatological information will answer the first question; antenna beamwidth and a path profile will answer the second.

After considering the concepts discussed above, a path length of one to two kilometers was decided upon for the VPI&SU 17.65 GHz ground link. Many hours of surveying finally resulted in the discovery of a 1.43 kilometer west to east path. The transmitter was installed in a small building mounted on telephone poles and located in a pasture on the west end of campus. The receiver was placed in the heating penthouse of McBryde Hall located in the main campus. Figure 1.1[4] is a profile of the 1.43 kilometer path. Notice that the one degree beamwidth eliminates the possibility of ground reflections.

Discussions with a local meteorologist convinced project personnel that rainfall rates of 12.5 mm/hr. to 150.0 mm/hr. would be observed with most local thunderstorms. On one rare occasion, however, a 198.6 mm/hr.

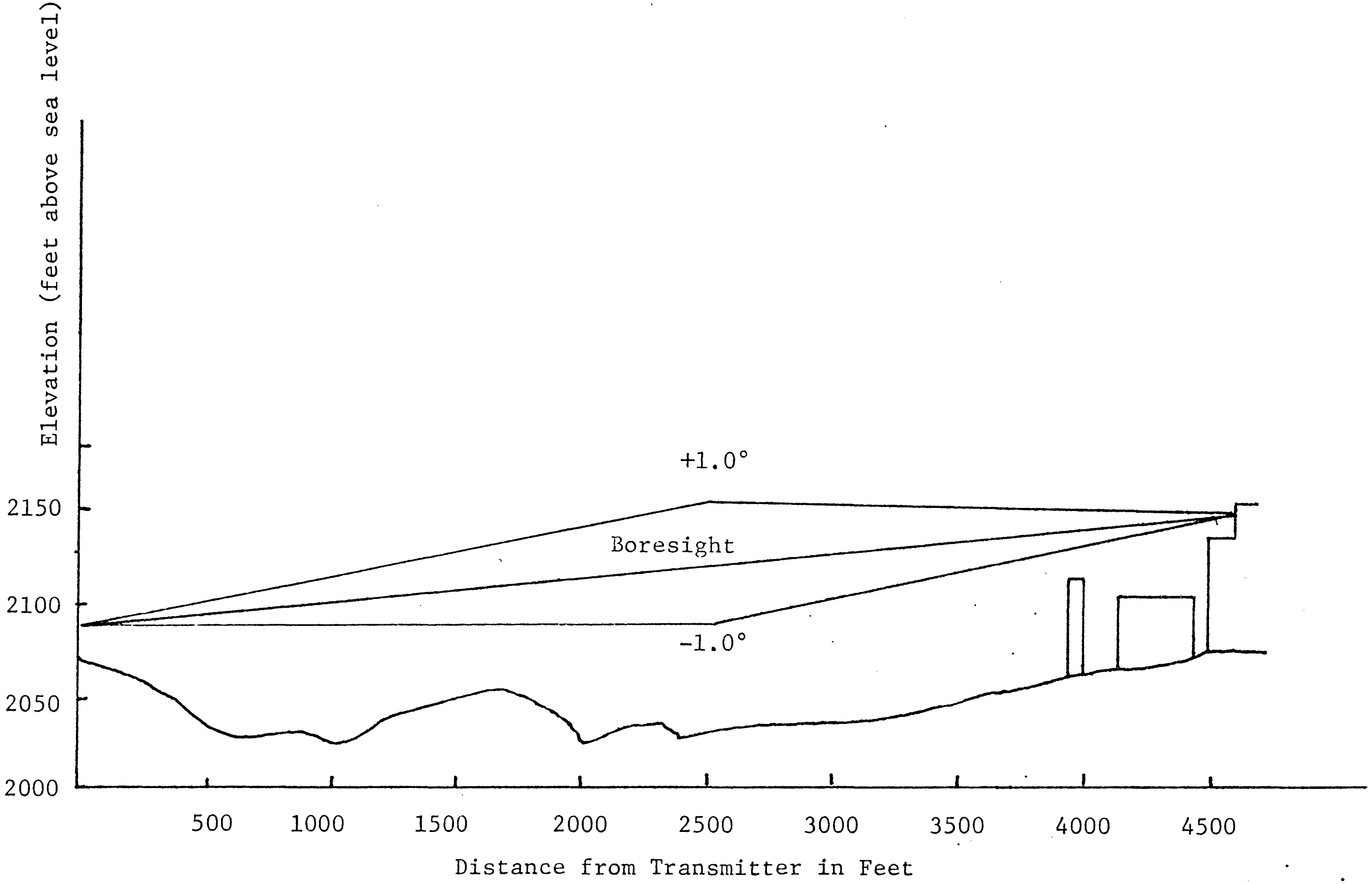


Figure 1.1. Path Profile

rate was observed.

Now that the path is well defined, it is necessary to calculate the expected values to be measured. Values of attenuation can be extrapolated from Figure 1.2 . The frequency of operation is 17.65 GHz. For a rain rate of 12.5 mm/hr., the expected attenuation is 1.0 dB/km. For 150.0 mm/hr., the expected attenuation is 13.8 dB/km. Below are the attenuations for this specific path.

1.43 dB @ 12.5 mm/hr.

19.73 dB @ 150.0 mm/hr.

This implies that the receiver must have at least a 20.0 dB dynamic range.

Calculating expected cross-polarization levels for this path is more complicated, but well explained by Thomas. The following two examples are calculations for the cross-polarization levels at 12.5 mm/hr. rain rate and 150.0 mm/hr. using the VPI&SU path length of 1.43 km. Figure 1.3 represents depolarization by differential attenuation. The major and minor axes refer to an oblate raindrop, the canting angle of the raindrop is 0°, and the transmitted polarization is plus 45° linear.

<u>12.5 mm/hr. rainfall rate</u>

From Thomas:

attenuation at 35 GHz = 2.81 dB/km (minor axis)

= 3.21 dB/km (major axis)

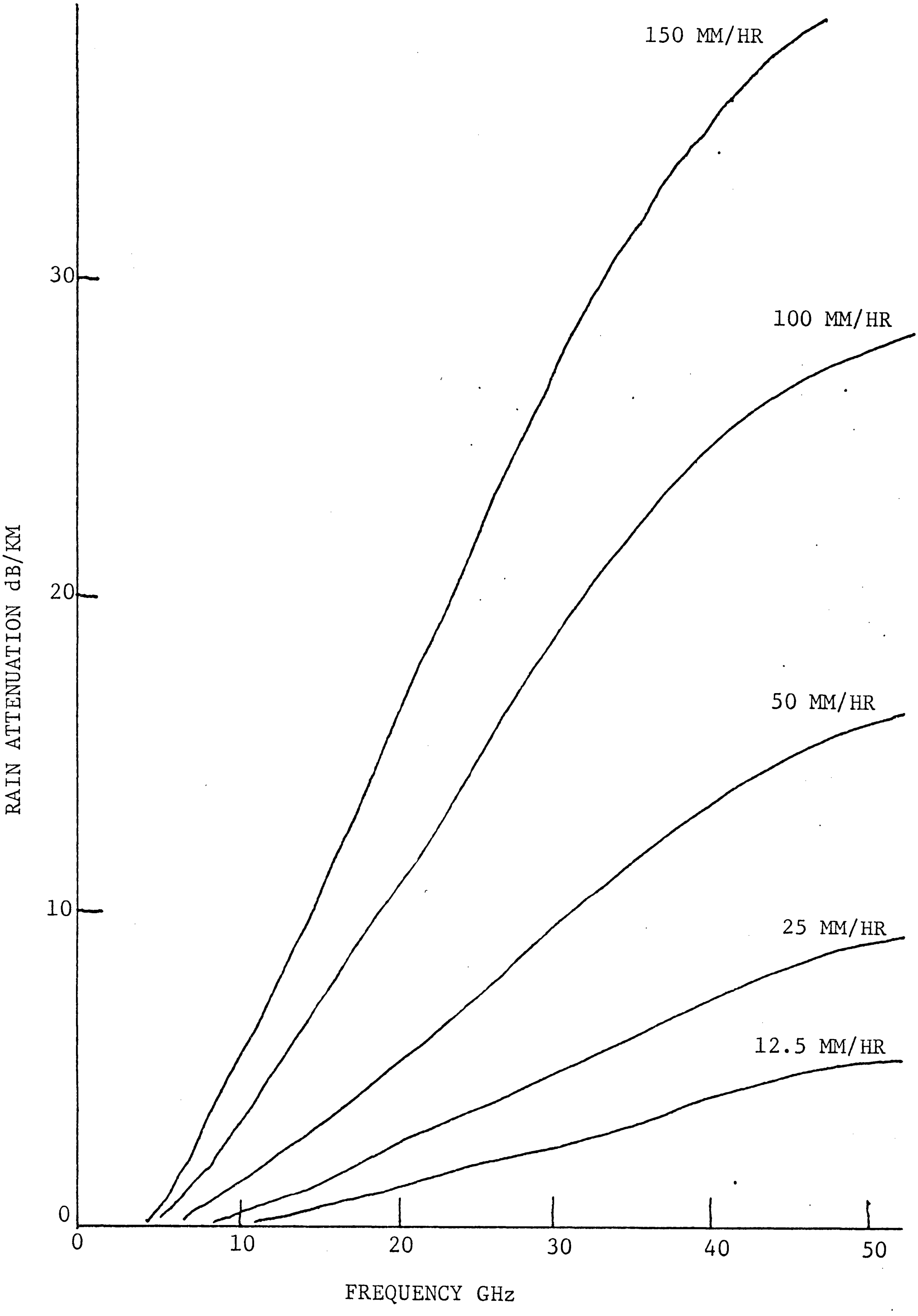


Figure 1.2. Rain-induced Attenuation

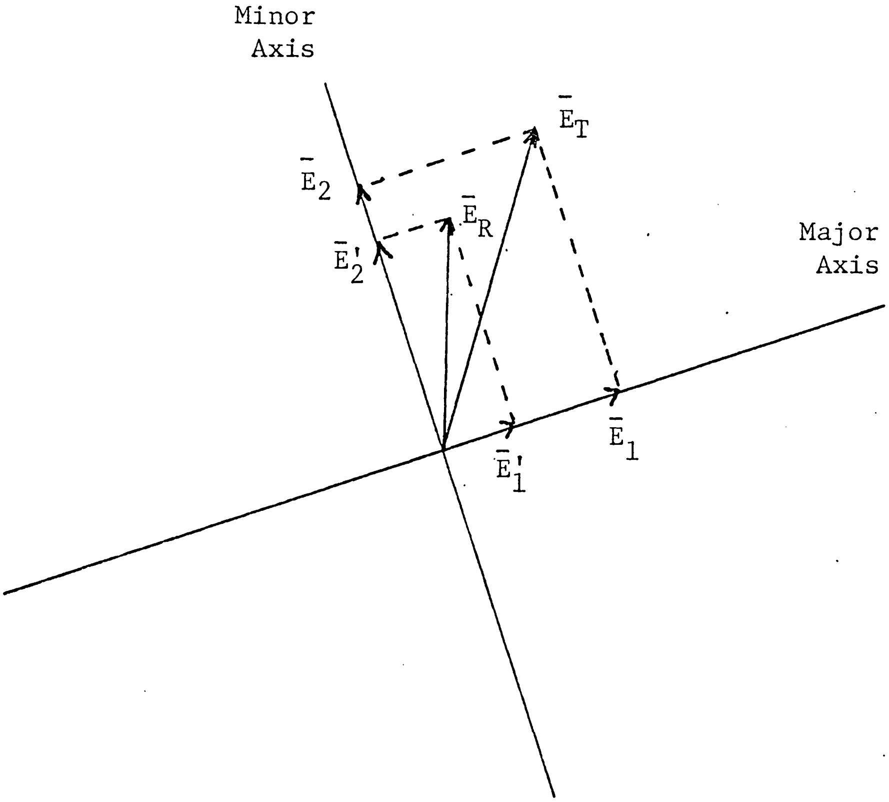


Figure 1.3. Depolarization by Differential Attenuation

attenuation at 17.65 GHz/attenuation at 35 GHz = 0.33

attenuation at 17.65 GHz = 0.94 dB/km (minor axis)

= 1.07 dB/km (major axis)

attenuation over 1.43 km path = 1.34 dB (minor axis)

1.53 dB (major axis)

$E_T = \sqrt{2}$

$E_{T_1} = 1.0$

$E_{T_2} = 1.0$

$20 \log {}^{E}R_1/{}^{E}T_1 = -1.53$

${}^{E}R_1/{}^{E}T_1 = 0.858$

$E_{R_1} = 0.858$

similarly

$E_{R_2} = 0.840$

Figure 1.4 shows the depolarized received signal relative to the orthogonal receive antennas.

$E_{RM} = \sqrt{2}\ (0.858) + \sqrt{2}\ (0.840) = 2.4$

$E_{RX} = \sqrt{2}\ (0.858) - \sqrt{2}\ (0.840) = 0.025$

$XPOL = 20 \log({}^{E}RX/{}^{E}RM) = -39.49$ dB

<u>150.0 mm/hr. rainfall rate</u>

attenuation at 35 GHz = 27.0 dB/km (minor axis)

= 31.6 dB/km (major axis)

attenuation at 17.65 GHz/attenuation at 35 GHz = 0.44

attenuation over 1.43 km path = 17.0 dB (minor axis)

= 19.9 dB (major axis)

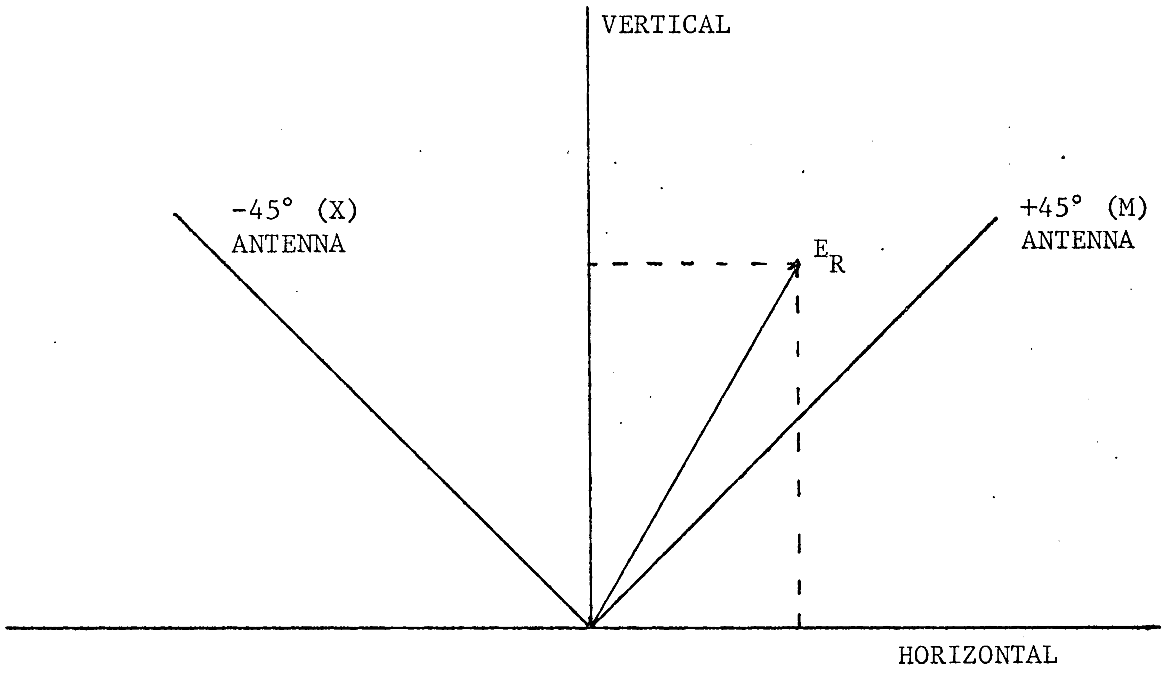


Figure 1.4. Received Depolarized Signal

$$20 \log (E_{R_1}/E_{T_1}) = -19.9$$

$$E_{R_1}/E_{T_1} = 0.142$$

$$E_{R_1} = 0.142$$

similarly

$$E_{R_2} = 0.101$$

$$E_{RM} = \sqrt{2}\ (0.142) + \sqrt{2}\ (0.101) = 0.343$$

$$E_{RX} = \sqrt{2}\ (0.142) - \sqrt{2}\ (0.101) = 0.058$$

$$XPOL = 20 \log (E_{RX}/E_{RM}) = -15.46 \text{ dB}$$

As the above calculations indicate, the receiver must have a dynamic range of at least 41 dB if cross-polarization measurements are to be made at the lower rainfall rates. A requirement of a 40 dB polarization isolation is also apparent, and can be met by a modern day receiver without difficulty. However, the limiting factor of polarization isolation at millimeter wavelengths is the antenna. At 17.65 GHz, a polarization isolation of 30.0 dB was the maximum value promised by any manufacturer in 1972. Fortunately, a polarization isolation of 51.0 dB was observed when the VPI&SU ground link experiment was first tested. If the path length had been any shorter, the lower rainfall rate data would have been erroneous for a polarization isolation of 40.0 dB.

1.3 Functions of the RF System

Attenuation measurements require relatively simple RF systems. A single channel receiver with the proper dynamic range, and a single channel transmitter are sufficient.

The transmitter, although single channel, should have the capability of either switching the RF to a matched load or attenuating the RF. This is convenient for system testing as well as being a good safety precaution. Repeated shutting down of the transmitting source decreases its life. A method for monitoring output power should also be included with the transmitter.

The receiver, as stated before, must have the necessary dynamic range. It should also have a transfer function that is simple and allows for accurate data acquisition.

Cross-polarization measurements require a two channel system with proper dynamic range and polarization isolation. The orthogonal channels can be designed to share certain components; this greatly reduces the cost.

The transmitter should consist of a single source so that any change in source power will not cause a synthetic change in the observed cross-polarization level. A single source also allows for easier phase or differential phase measurements. Since simultaneous cross-polarization measurements between two orthogonal channels are desirable, each channel must have the capability of transmitting either into the antenna or into a matched load.

The receiver should consist of two orthogonal channels that share a common local oscillator. The detecting devices should have the capability of measuring the magnitude and phase of the received signal. Again, a polarization isolation greater than the expected cross-polarization level is essential.

The VPI&SU 17.65 GHz ground link was designed to generate any of three types of data: (1) simultaneous attenuation for two orthogonal linear polarizations, (2) plus 45° attenuation and plus 45° to minus 45° cross-polarization, and (3) minus 45° attenuation and minus 45° to plus 45° cross-polarization. The plus 45° and minus 45° polarizations were used so that the depolarization effect would be maximized. These three types of data required the transmitter to operate in either of three modes: (1) plus channel transmitting-minus channel off, (2) minus channel transmitting-plus channel off, and (3) both plus and minus channels transmitting. The receiver only required one mode: both plus and minus channels receiving at all times.

1.4 Control of the Experiment

Rain-induced attenuation and depolarization are observable only a limited amount of time. The storms that cause the phenomena are unpredictable on a long range basis, and often occur at inconvenient times of the day. For attenuation experiments, this problem is not so severe; depolarization experiments that require remote switching of channels are more of a problem. For both experiments, it makes sense for the switching and data acquisition to be rain induced.

Loss of data may result when line power is lost during thunderstorms. For this reason, an independent back up power system should parallel the line power. Provisions for automatic switch over in case of a power failure should be included.

The VPI&SU ground link uses a Raytheon PB-440 computer to control the experiment. The experimental control program initiates the transmitter switching sequence as well as the data acquisition sequence when precipitation is detected. Precipitation is detected by one of the five tipping bucket rain gauges along the 1.43 km path. When the precipitation falls below 2 mm/hr., the sequence is halted. Emergency power is provided by a bank of aircraft batteries at the transmitter, receiver, and computer control location.

1.5 Summary of Design Criteria

Below are listed all the design criteria established at this point. The design of the system will follow in the next two chapters.

Frequency: 17.65 GHz

Path Length: 1.43 km

Transmitter

1. Operating independent channels: 2(+45° and -45° polarization)
2. Switching capability: transmit or no transmit remotely selected for each channel
3. Polarization isolation: > 40.0 dB

Receiver

1. Operating independent channels: 2(+45° and -45° polarization)
2. Polarization isolation: > 40.0 dB
3. Dynamic range: > 41.0 dB
4. Easily interpreted transfer function

SECTION 2

RECEIVER

2.1 Scope of Section

Presented in this section are typical receivers for attenuation and depolarization measurements, design calculations for the VPI&SU 17.65 GHz transmitter, and suggested improvements.

2.2 Typical Receivers

Once the path is defined, the receiver design is primary. Optimum receiver performance is obtained easily if one is not working under the restriction of a specific received signal level. This restriction fixes the upper bound of the dynamic range and forces the designer to find hardware that will fit the situation. It is simpler to design the receiver and then provide the proper transmitted power.

Figure 2.1 is a block diagram of a receiver that will measure attenuation. Single conversion is used because it is economical, introduces less noise, and is easily accomplished with available millimeter wave components. The RF amplifier and mixer are usually found commercially in a single "black box." Noise associated with wide bandwidths and high noise figures is a major cause of shortened receiver dynamic range. Bandwidths as low as 10 MHz are available with most commercial millimeter wave mixer-preamplifiers. Typical noise figures are from 9.0 to 10.0 dB. The local oscillator must be stable because of the narrow bandwidth requirement. A 50% savings is usually realized when mechanical tuning is chosen over voltage tuning; voltage tuned

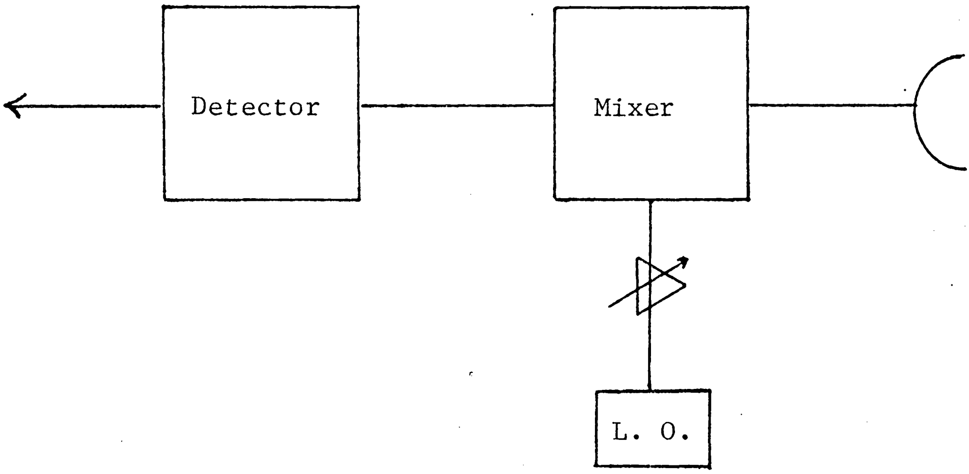


Figure 2.1. Attenuation Receiver

oscillators also require more expensive and stable power supplies. Detector choice is based mainly on the transmission mode used, but a linear transfer function will result in easier data analysis.

Figure 2.2 is a block diagram of a dual channel receiver used for cross-polarization measurements. The mixers, preamplifiers, local oscillator, and detectors are identical to the components used in the attenuation receiver. The local oscillator is shared by both channels, which greatly reduces cost and tuning difficulties. The relative cost of the local oscillator allows the addition of another channel for about 70% of the cost of a single channel receiver.

Figure 2.3 is a block diagram of the VPI&SU 17.65 GHz, CW, receiver. The isolators insure polarization isolation, and the attenuators control local oscillator power to the mixers. The use of uncalibrated attenuators here will save about $300.00 per attenuator.

2.3 Choosing Receiver Components

The elimination of cost and noise due to a transmission line between a pre-amplifier and a mixer warranted the use of commercially available mixer-preamplifiers for the VPI&SU receiver. A balanced mixer with an orthomode coupling mechanism was chosen because of its high isolation between the local oscillator port and the RF port.[5] Local oscillator noise suppression also prompted the use of a balanced mixer[6], because local oscillator noise reduces the dynamic range of the receiver.

The mixer-preamplifier chosen was an RHG MP015/2C. The specifications are listed below.

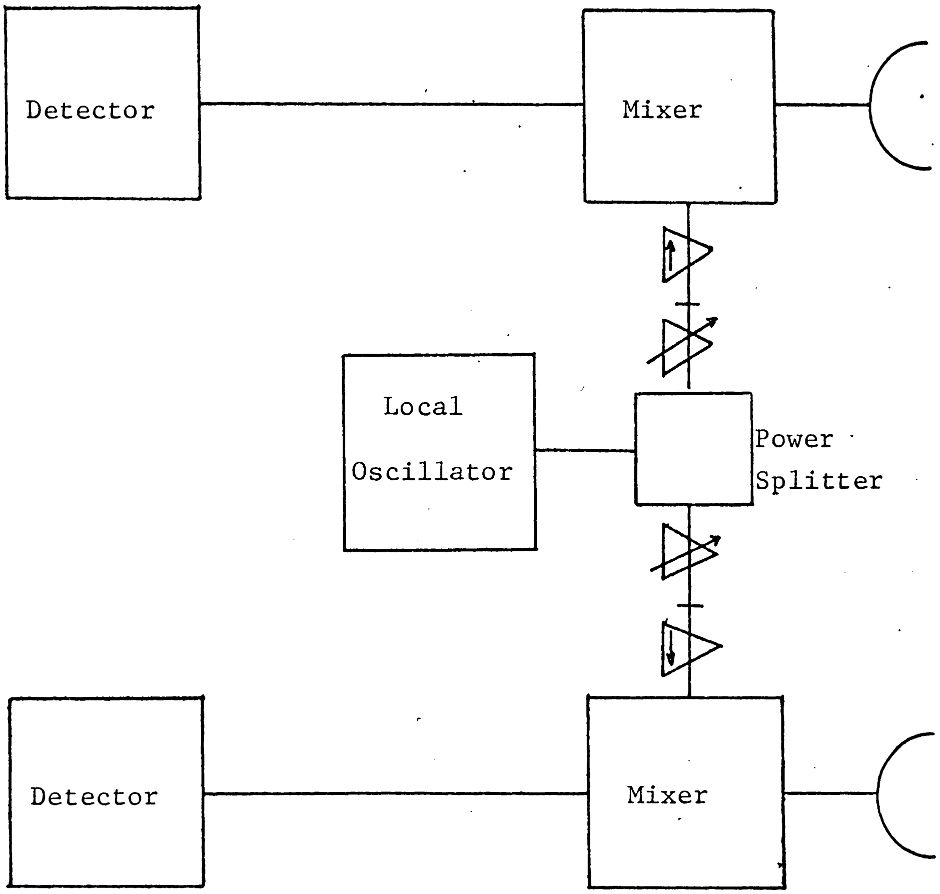


Figure 2.2. Depolarization Receiver

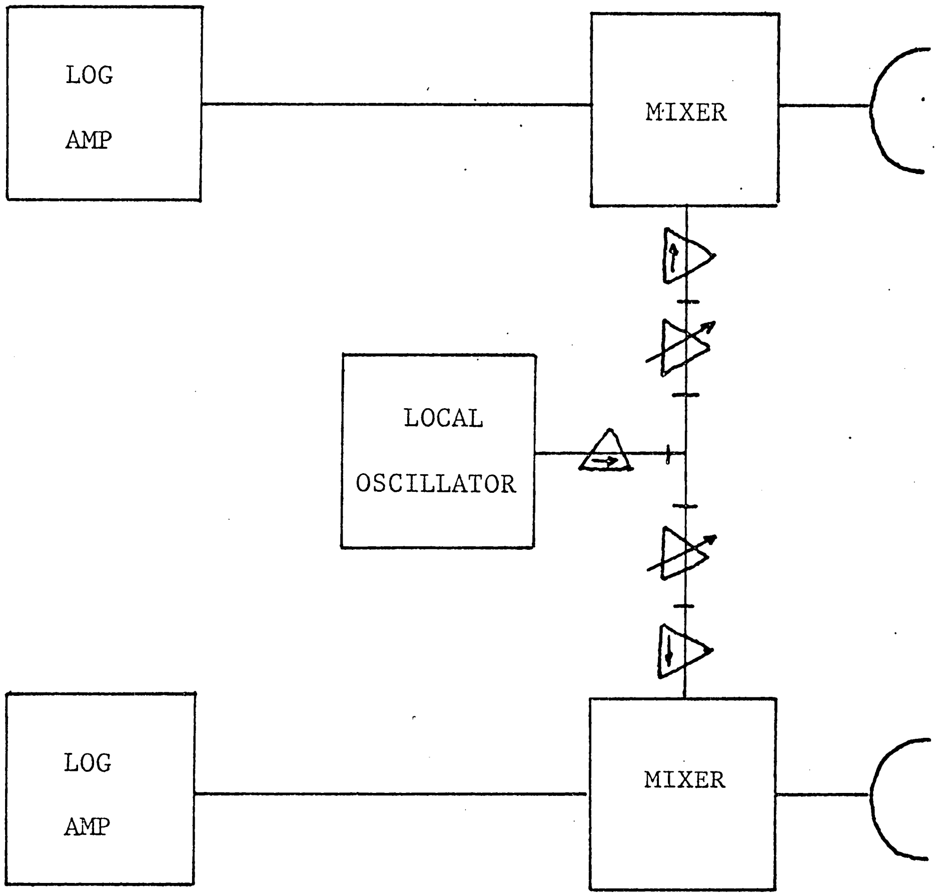


Figure 2.3. VPI & SU Receiver

Gain: 25 dB

LO Injection: 0 to +3 dBm

LO to RF Isolation: 20 dB

Input VSWR: 3/1

IF: 30 MHz

IF Bandwidth: 10 MHz

Noise Figure: 9.8 dB

An ideal figure can now be placed on the receiver sensitivity. This sensitivity will be a best case value and will be adjusted by local oscillator noise.

$S = -174\ \text{dBm} + 10\log(BWXF)$ [7]

S = CW sensitivity in dBm

BW = IF bandwidth in H_z

F = noise figure expressed as a ratio

Diode conversion loss is included in the noise figure.

$S = -94.2\ \text{dBm}$

The orthomode coupling system does introduce the problem of a 3 to 1 VSWR. The mixer must receive a 0 to +3 dBm local oscillator signal above the reflected local oscillator power. Below is a calculation of minimum LO power required for proper operation.

$|p|$ = magnitude of the reflection coefficient

$|p| = (VSWR - 1)/(VSWR + 1) = 1/2$

$t+r = 1.0$

$t \equiv$ transmitted power coefficient

$r \equiv$ reflected power coefficient

$r = |p|^2 = 1/4$

$t = 3/4$

$p_{LO} \equiv$ local oscillator power

$p_{LO}t = 1$ mw

$p_{LO} = 4/3$ mw (minimum value)

$p_{LO} = 8/3$ mw (maximum value)

p_{LO}(total) $= 16/3$ mw (maximum value)

Since commercial specifications tend to reflect the best possible values of VSWR, it is best to buy more LO power than is needed and then put an attenuator in series with the mixer LO input. This also allows the receiver to operate longer if the LO power decreases with age.

Receiver stability is almost completely dependent upon local oscillator stability with a fixed frequency CW receiver. The bandwidth of the receiver is 10 MHz and if the LO drifts 5.0 MHz or more, an attenuation measurement error of at least 3 dB would occur. Cross-polarization data would not be erroneous because each channel would fade equally. The danger to cross-polarization measurements results from a loss in dynamic range. As the LO drifts, the IF will drift out of the bandwidth and the detector output will drop. This forces the upper end of the dynamic range to move towards the lower end and jeopardizes the lower rainfall rate data. Below is a calculation of required LO stability.

Frequency = 17.62 GHz

$$\text{Stability} = \pm(BW/2)(100/F) = \pm \frac{.5}{17.62} = \pm 0.0284\%$$

This value of stability must be good over the temperature range the LO will experience. If temperatures are extreme, an environmental chamber may be more economical than buying an LO that is stable over the extreme temperature range.

Noise generated by the LO causes a reduction in the dynamic range of the receiver, by causing a detector output when no RF is applied to the mixer. Noise problems can be minimized by choosing the most stable LO available and picking an IF bandwidth as small as possible for that stability. This also aids in tuning because the detector output will have a sharper maximum for the smaller bandwidths. The value for allowable LO noise will vary depending on the type of detector used, and for that reason, a more detailed discussion of LO noise will be presented after the section on detectors. Below is a list of LO specifications defined to this point.

Frequency: 17.62 GHz
Stability: ± 0.0284%
Power: 4/3 to 8/3 mw (per channel)
Tuning: Mechanical

Detectors

As stated before, the dynamic range of the receiver must be greater than 42 dB, and the transfer function should be as elementary as possible. For these two reasons, the logarithmic amplifier is an ideal detector for attenuation and cross-polarization measurements. Figure 2.4 represents the input vs output characteristic of an RHG LST 3010 MAT log amplifier chosen for the VPI&SU receiver. The linear D.C. output vs input dBm is "tailor made" for attenuation or cross-polarization

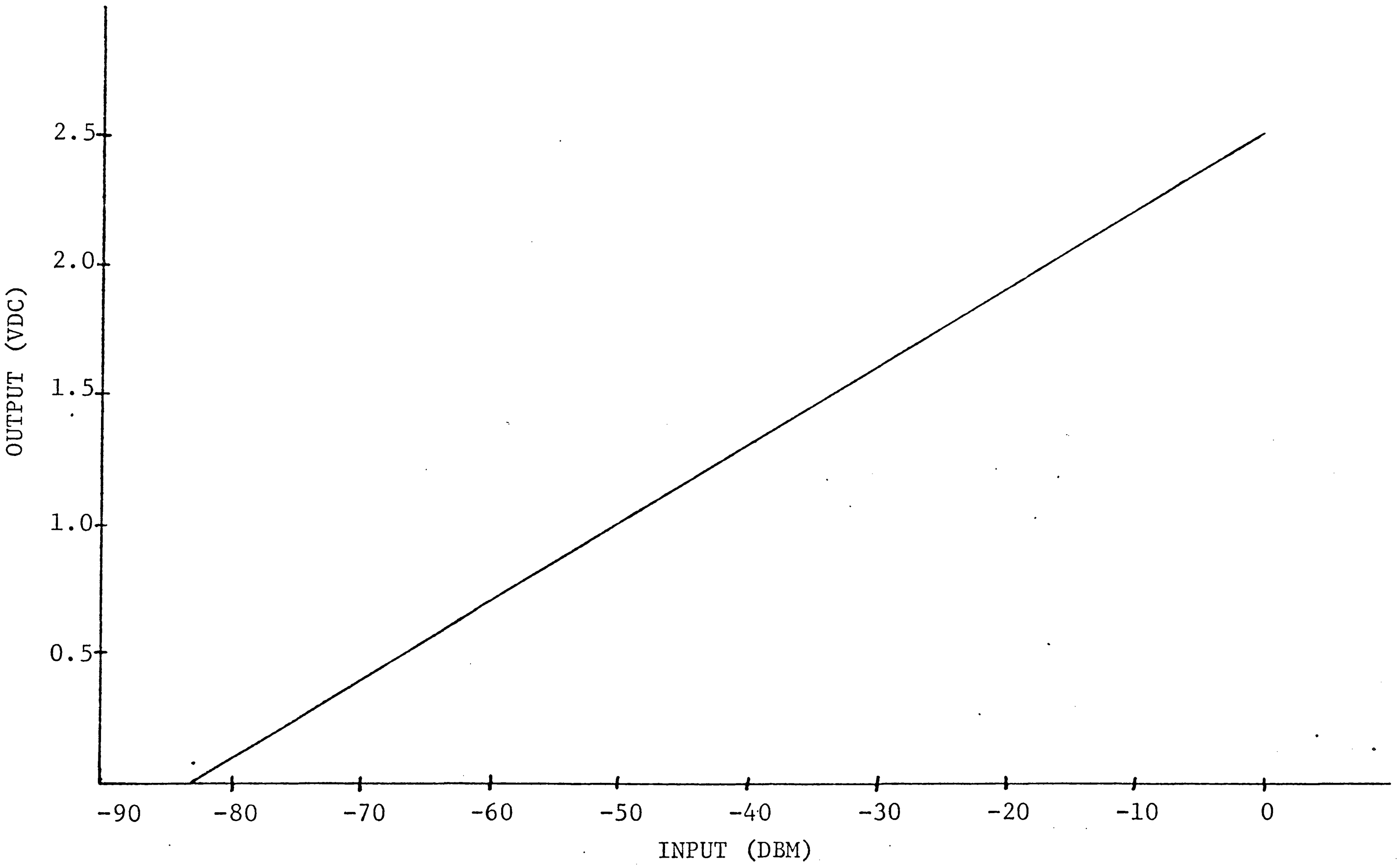


Figure 2.4. Logarithmic Amplifier

measurements. Below is a list of the RHG log amplifier specifications.

Frequency:	30 MHz
Bandwidth:	10 MHz
Input Impedance:	50 Ω
Input VSWR:	< 1.5-1
Dynamic range:	> 80 dB
Log accuracy:	± 1 dB over 80 dB range

It is now possible with the aid of Figure 2.4 to calculate the maximum allowable LO noise. A dynamic range of 50 dB was used instead of 42 to insure that all the data is observed. A 50 dB dynamic range corresponds to a -50.0 dBm LO noise signal.

DETECTOR INPUT VSWR = 1.5 to 1

$$|p| = \frac{1.5-1}{1.5+1} = \frac{0.5}{2.5} = 1/5$$

$$t + r = 1.0$$

$$r = |p|^2 = \frac{1}{25}$$

$$t = 24/25$$

P_{ND} = noise power incident to the detector = $\frac{25}{24}(10^{-5})$ mw

$$P_{ND} = -49.8 \text{ dBm}$$

IF gain = 25 dB

P_{NLO} = -49.8 dBm - 25 dB = -74.9 dBm ≡ local oscillator noise power.

Since this is a two-channel receiver, the total allowable LO noise is - 71.9 dBm.

Shurmer[8] suggests the use of Gunn oscillators for local oscillators when the IF is around 30 MHz because of their low noise properties.

The Gunn oscillator is very economical as well because it can be mechanically tuned and requires only a low DC voltage for power.

The local oscillator chosen for the VPI&SU receiver is an RHG G01K131 mechanically tuned Gunn oscillator with the following specifications.

Frequency:	17.62 GHz
Stability:	15 to 35° C
Noise:	- 110 dB
Power:	25 mw

The output of the detector is 0.5 VDC when full LO power is allowed to the mixer and no RF power is present at the mixer. This sets a lower limit on the dynamic range of 68 dB. When the attenuators were set for 4/3 of a milliwatt LO power to each channel, the detector output was 0.4 VDC corresponding to a 71.4 dB dynamic range.

The RHG mixers used have an LO to RF isolation of 20 dB. This value is far short of the 42.0 dB polarization isolation needed as predicted in Section 1. A 24 dB isolator was placed in each channel to insure the minimum polarization isolation.

$$PI = I_I + T_I + M_I + A_I$$

PI = polarization isolation

I_I = isolator isolation = 24 dB

T_I = E plane tee isolation = 3.0 dB

M_I = mixer isolation = 20.0 dB

A_I = attenuator isolation = (0 to 25 dB)

PI = 47 dB (minimum value)

= 72 dB (maximum value)

The 24 dB isolator at the LO output is strictly for VSWR protection for the L.O., because a lossless reciprocal 3-port can never be completely non-reflecting.[9]

The two attenuators are used for adjusting local oscillator power to the mixer. The local oscillator power is 25 mw and each channel requires at least 4/3 mw for proper mixer operation. The amount of attenuation required is given by A_{LO}.

$$A_{LO} = 10 \log \left(\frac{25}{2} \cdot \frac{3}{4}\right) = 10 \log \left(\frac{75}{8}\right)$$

$$A_{LO} = 9.75 \text{ dB.}$$

Commercial uncalibrated attenuators for K_u band are available in 0 to 25 dB varieties or higher, so a 0 to 25 dB uncalibrated attenuator was chosen for each channel. Since LO power to the mixer is the important parameter, the attenuator setting is made by monitoring power from the attenuator. The use of uncalibrated attenuators saved the project $600.00.

The E-plane tee splits the local oscillator power. It is the most economical device available for that purpose, but it does cause the phase of each output leg to be 180° apart. Figure 3.6 represents an E-plane tee and its scattering matrix. Ports 1 & 2 are the mixer legs while port 3 is the local oscillator leg.

$$\begin{vmatrix} b_1 \\ b_2 \\ b_3 \end{vmatrix} = 1/2 \begin{vmatrix} 1 & 1 & \sqrt{2} \\ 1 & 1 & -\sqrt{2} \\ \sqrt{2} & -\sqrt{2} & 0 \end{vmatrix} \begin{vmatrix} a_1 \\ a_2 \\ a_3 \end{vmatrix}$$

If ports 1 and 2 are matched then a_1 and a_2 are both zero.

$$b_1 = \frac{\sqrt{2}}{2} a_3$$

$$b_2 = -\frac{\sqrt{2}}{2} a_3$$

From these calculations it can be seen that the voltage at port 1 is 180° out of phase with the voltage at port 2. After filtering, the mixer outputs are:

$$a_2 e_{LO} e_{RF} \cos([\omega_{SIG} - \omega_{LO}]t) \qquad \text{(port 1)}$$

$$a_2 e_{LO} e_{SIG} \cos([\omega_{SIG} - \omega_{LO}]t - \phi) \qquad \text{(port 2)}$$

$\phi = \pi$ for E-plane tee

Since the detectors respond to input dBm, the phase of the mixer output is of no concern.

2.4 Suggested Improvements

The addition of a calibrated phase shifter in one channel would allow the experimentor to set the clear weather phase difference between channels to 0°. This would greatly simplify received signal phase measurements.

2.5 Final Receiver Specifications

Figure 2.5 is the transfer function for the VPI&SU 17.65 GHz receiver. Both channels are identically calibrated. Below is a list of the final receiver specifications.

Dynamic Range:	71.4 dB
Channel Isolation:	> 60 dB

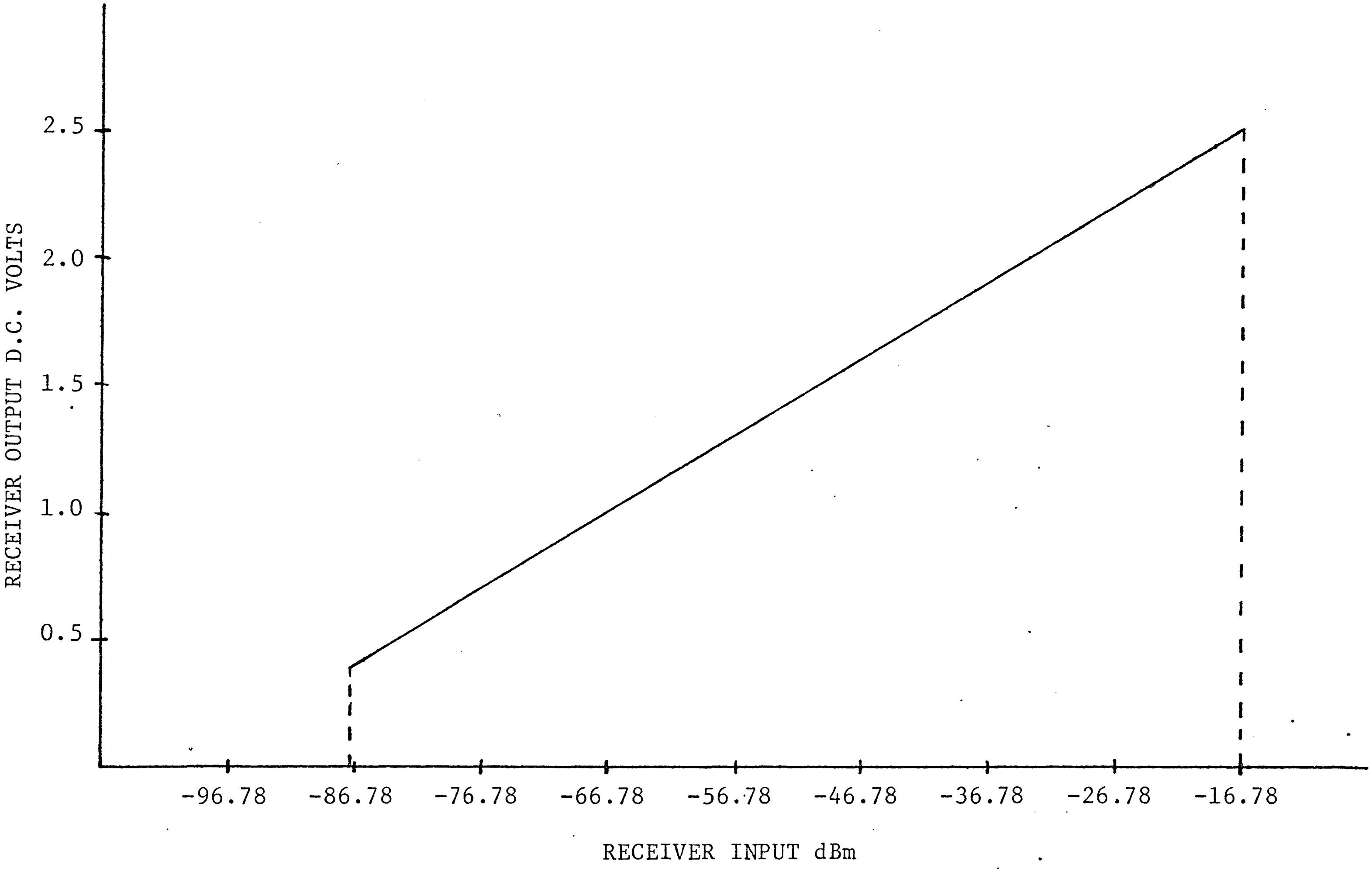


Figure 2.5. VPI & SU Receiver Transfer Function

SECTION 3

TRANSMITTER

3.1 Scope of Section

Presented in this section are typical transmitters for attenuation and depolarization measurements, design calculations for the VPI&SU 17.65 GHz transmitter, and suggested improvements.

3.2 Typical Transmitters

Figure 3.1 is a block diagram of a typical transmitter for attenuation measurements. The source should be stable in both frequency and power. If the source is capable of delivering more than the required power, an uncalibrated attenuator can be used to reduce the transmitter output to the design level and to hold it there as the source ages. An isolator should be used to protect the source from a high VSWR encountered during switching unless one is provided internally with the source. A directional coupler and a power meter will allow continuous monitoring of the output power. It is often convenient during antenna alignment or receiver checks to shut down the transmitter power. A waveguide switch and a matched load will allow the transmitter power to be dissipated safely when so desired.

Figure 3.2 is a block diagram of a typical transmitter for cross-polarization measurements. The components are identical except for the power splitting device. The VPI&SU 17.65 GHz transmitter is identical to this except that a 3 dB coupler is used as the power splitting device and an uncalibrated attenuator is placed in one channel to insure equal

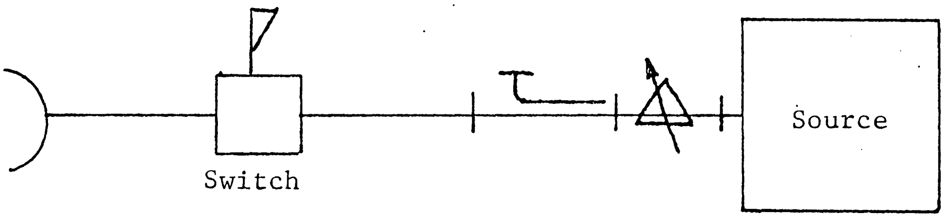


Figure 3.1. Attenuation Transmitter

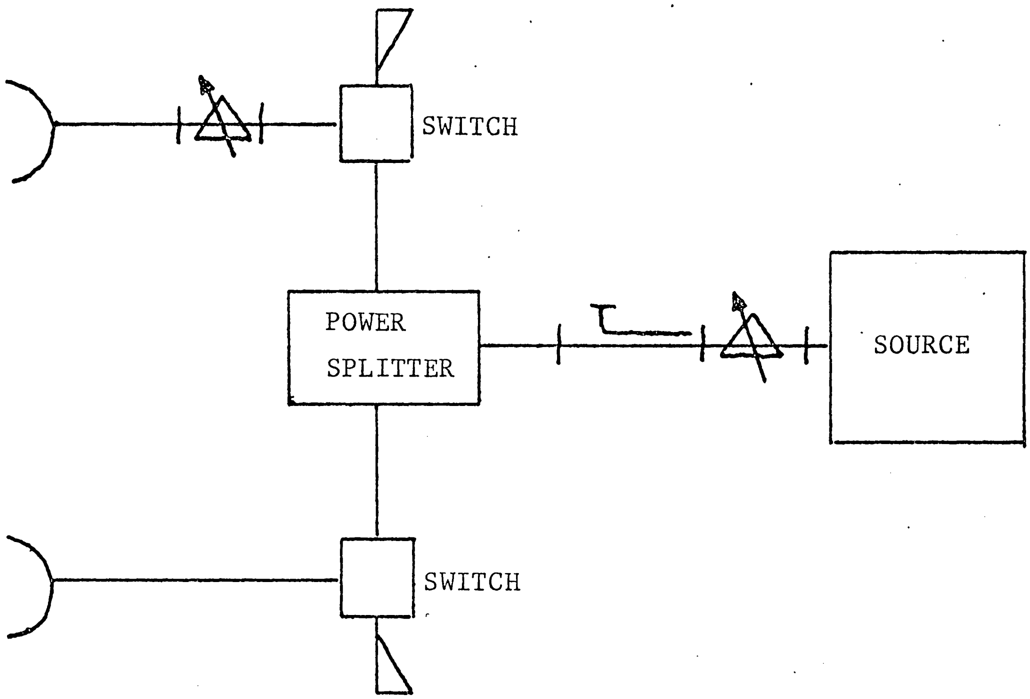


Figure 3.2. Depolarization Transmitter

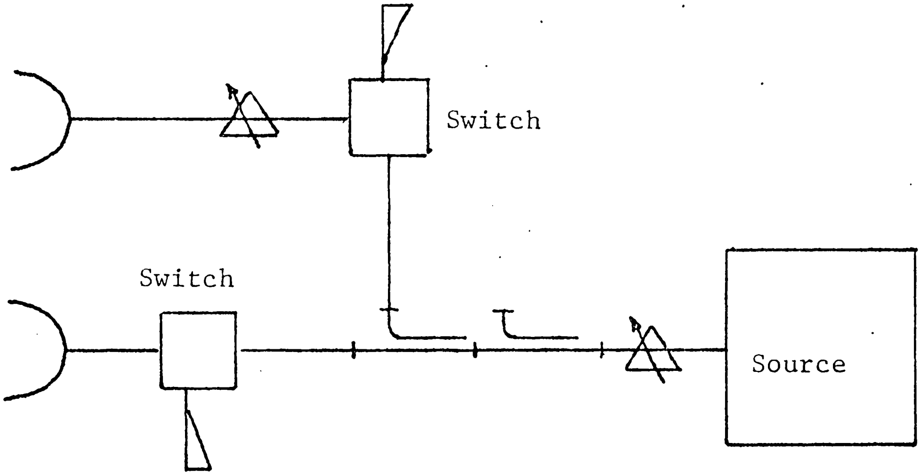


Figure 3.3. VPI&SU Transmitter

outputs.

3.3 Necessary Transmitter Power and Stability

The power required depends upon receiver saturation·level, path loss, antenna gain, and transmission line loss. Below is a calculation of the required transmitter power for the VPI&SU 17.65 GHz transmitter.

$$L \equiv \text{path loss} = 21.98 + 20 \log (r/\lambda) \qquad 10$$

$r \equiv$ path length

$\lambda \equiv$ wavelength

$\lambda = C/F = 0.017$ m

$L = 120.48$ dB

$P_T \equiv$ power transmitted $= P_R + L - G_{AT}$

$P_R \equiv$ necessary receiver input power $= -16.78$ dBm

$G_{AT} \equiv$ total antenna gain $= 90$ dB

$P_T = 13.7$ dBm or 23.44 mw

For a two channel transmitter, the total output power must be 46.88 mw.

The stability of the source at the required power level is just as important as local oscillator stability. Below is a calculation of required source stability for the VPI&SU 17.65 GHz source.

$S \equiv$ stability $= \pm\ (BW/2)\ (100/F)$

$BW \equiv$ bandwidth

$F \equiv$ frequency

$S = \pm\ (.01/2)\ (100/17.65) = \pm\ 0.028\%$

3.4 Component Selection

The source chosen is an RDL POOK(3) crystal oscillator and varactor chain multiplier. The specifications are listed below.

Frequency: 17.65 GHz

Stability: ± 0.005%

Power Output: 70 mw minimum

Temperature: 0 to 50° C

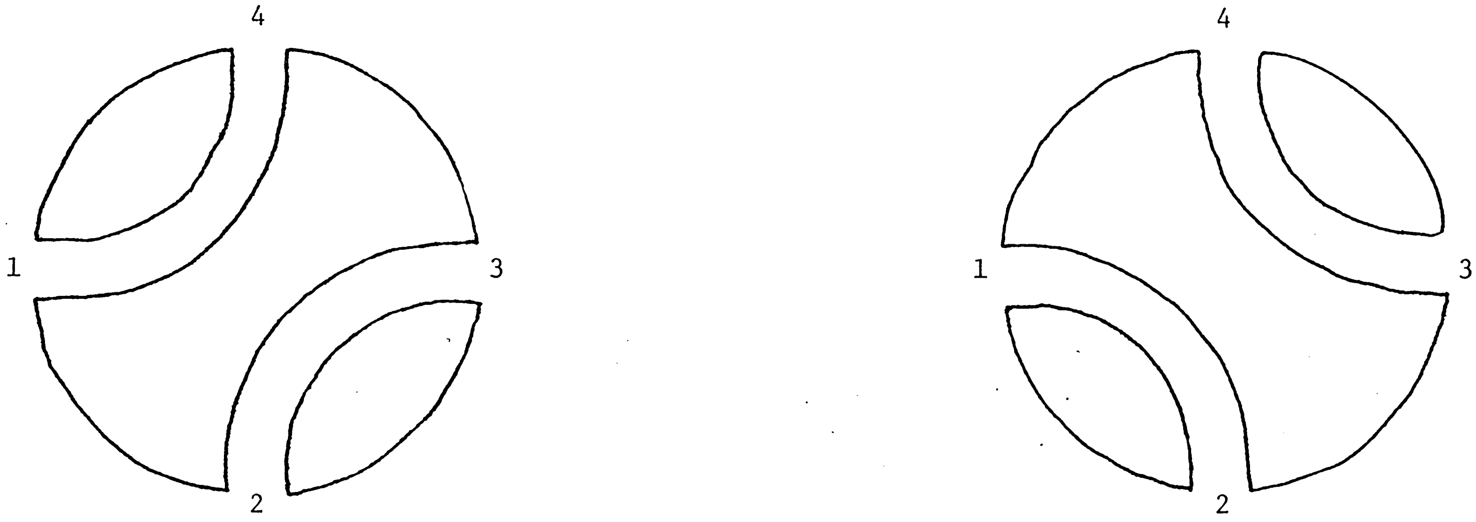
Spurious Noise: < -40.0 dB

Mechanical waveguide switches were chosen because of their high isolation between ports. The isolation must be as great or greater than the polarization isolation of the receiver or erroneous cross-polarization levels will be observed. The waveguide switches chosen were Waveline 777-E solenoid operated, double pole-double throw, current holding switches.

3.5 Transmission Line Components

A major concern in the design of the transmitter was the VSWR introduced by the waveguide switches during switching.

Figure 3.4 is a top view of a Waveline 777-E switch in the rest position. For this explanation port 1 is the source power input, port 4 is matched, and port 2 is the antenna feed. The 90° circular arc from port 1 to port 2 is 1.42 inches long. The dimension of the waveguide short wall is 0.311 inches. When the switch is activated, port 1 is fed to port 2 and port 4 is fed to port 3. As the cylinder moves, port 1 is shorted for 1.11 inches of the 1.42 inches of movement. If



90° Arc = 1.42"
Short Wall = 0.31"
Short = 1.11" or 78% of 90° Arc

Figure 3.4. Waveguide Switches

the cylinder moves at a uniform velocity for the 100 msec switching time, the short will last 78 msec. The short is not perfect however, and a VSWR reading in 78 msec is difficult to obtain. In order to get an estimated value of the VSWR, a shorting plate was placed across port 4 and a slotted line was placed in series with port 1. With the source transmitting and the switch deactivated, the VSWR was 25.0. Under operating conditions, the short will not be this good because of the small clearance between the rotating cylinder and the four ports.

$$|p| = \frac{\text{VSWR-1}}{\text{VSWR+1}} = \frac{24}{26} = 0.923$$

$$r \equiv \text{reflected power coefficient} = |p|^2 = 0.852$$

$$P_R \equiv \text{power reflected} = r(\text{source power}) = 25\ r = 21.3\ \text{mw}$$

Not only must the source be protected from this reflected power, but the reflected power should not be coupled into the other channel. Below is an analysis of a 3 dB coupler used as the power splitter. Figure 3.5 represents a 3 dB coupler and its scattering matrix.

$$c^2 \equiv \text{coupling ratio} = 1/2 \text{ (for a 3 dB coupler)}$$

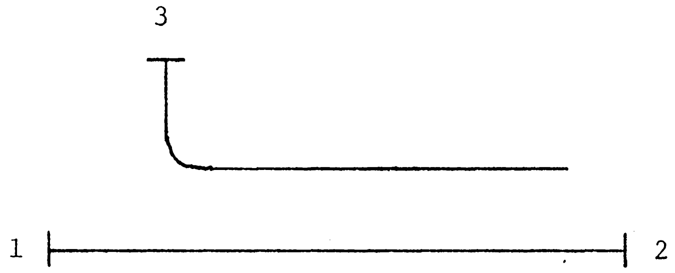
$$a_1 = \sqrt{50}$$

$$a_2 = 0 \text{ (part 2 terminated with a matched load)}$$

$$a_3 = \sqrt{21.3}\ \text{mw (voltage reflected when switch activates)}$$

$$\begin{vmatrix} b_1 \\ b_2 \\ b_3 \end{vmatrix} = \begin{vmatrix} 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\ 2 & 0 & 0 \\ 1/\sqrt{2} & 0 & 0 \end{vmatrix} \begin{vmatrix} \sqrt{50} \\ 0 \\ \sqrt{21.3} \end{vmatrix}$$

$$b_1 = \frac{\sqrt{21.3}}{\sqrt{2}}$$



$$\begin{matrix} 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & 0 & 0 \\ 1/\sqrt{2} & 0 & 0 \end{matrix}$$

Figure 3.5. 3dB Coupler and Scattering Matrix

$P_{RS} \equiv$ power reflected to source = 10.65 mw

When both switches are activated simultaneously, the reflected power will be 21.2 mw.

$$50\ r = 21.3$$

$$r = 0.426 = |p|^2$$

$$|p| = 0.653$$

$$\text{VSWR} = \frac{1 + |p|}{1 - |p|} = 4.76$$

Discussions with RDL technicians convinced project personnel that the RDL POOK(3) source would withstand a 4.76 VSWR for 78 msec.

The 3 dB coupler also provides excellent channel isolation for power reflected during switching.

$$\begin{vmatrix} b_1 \\ b_2 \\ b_3 \end{vmatrix} = \begin{vmatrix} 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & 0 & 0 \\ 1/\sqrt{2} & 0 & 0 \end{vmatrix} \begin{vmatrix} a_1 \\ a_2 \\ a_3 \end{vmatrix}$$

$b_2 = \dfrac{a_1}{\sqrt{2}}$ (contains no reflections from part 3)

$b_3 = \dfrac{a_1}{\sqrt{2}}$ (contains no reflections from part 2)

The 40.0 dB coupler allows the source power to be continuously monitored. The coupling ratio was carefully checked for accuracy at 17.65 GHz and was found to be 40.0 dB.

The attenuators used are uncalibrated with a range of 0 to 25 dB. The high values of attenuation were never used, but lower value variable attenuators were not available. The VSWR of each attenuator was 1.15 maximum.

3.6 Transmitter Performance

The VPI&SU 17.65 GHz transmitter was licensed in the spring of 1972 as a contract developmental station in the experimental radio service. It was assigned the call letters KQ2XOC. In accordance with FCC regulations, the transmitter source was provided with a remote "on-off" circuit located adjacent to the PB-440.

Below are the transmitter specifications measured during the final testing stage.

Frequency: 17.65 GHz ± 800 KHz

Power Output: 26 mw per channel

Isolation between channels: > 60 dB

VSWR: 1.1 (static condition)

The 26 mw value was the transmitter power required to produce a 2.5 volt receiver output. The calculated value was 23.44 mw. One source of error for this calculation is the actual antenna gain. The antenna gain measured by the manufacturer was 44.5 dB as compared to the estimated value used of 45.0 dB.

1.0 dbm is 1.25 mw

Actual required output power = 23.44+1.25 = 24.69 mw

3.7 Possible Transmitter Improvements

The addition of a phase shifter in one channel of the transmitter would allow for easier phase measurements between cross-polarized channels at the receiver. The phase shifter should be adjusted so that the received clear weather phase difference is 0 degrees.

In the VPI&SU 17.65 GHz experiment, data is taken 100 msec after a waveguide switch changes state. The possible VSWR of 25 has disappeared in this time. For this reason, the use of the 3 dB coupler as a splitter may be unwarranted. If the source is properly protected against a high VSWR, an E-plane tee would be more economical to use. Figure 3.6 represents an E-plane tee and the scattering matrix for an ideal E-plane tee. Part 3 is the source feed and parts 1 and 2 are the orthogonal channel feeds.

channel 1 switching:

$a_1 = \sqrt{21.3}$

$a_2 = 0$

$a_3 = \sqrt{50.0}$

$b_2 = -2.68$ or 7.23 mw

$b_2 = 3.26$ or 10.65 mw

channel 2 switching

$a_1 = 0$

$a_2 = -\sqrt{21.3}$

$a_3 = \sqrt{50}$

$b_1 = 2.68$ or 7.23 mw

$b_3 = -3.26$ or 10.65 mw

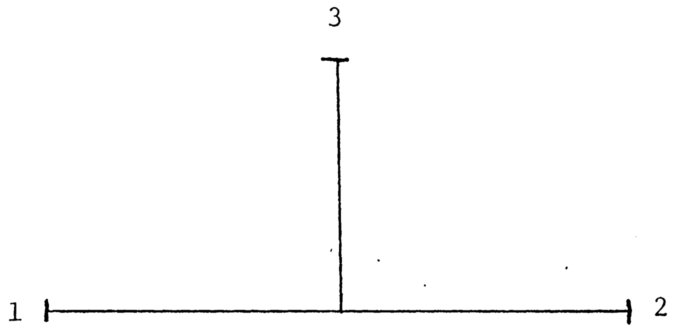
channel 1 and 2 switching:

$a_1 = \sqrt{21.3}$

$a_2 = -\sqrt{21.3}$

$a_3 = \sqrt{50.0}$

$b_3 = 6.53$ or 42.6 mw



$$1/2 \begin{vmatrix} 1 & 1 & \sqrt{2} \\ 1 & 1 & -\sqrt{2} \\ \sqrt{2} & -\sqrt{2} & 0 \end{vmatrix}$$

Figure 3.6. E-Plane T and Scattering Matrix

$$r = \frac{42.6}{50.0} = 0.853$$

$$r = |p|^2$$

$$|p| = 0.925$$

$$\text{VSWR} = \frac{1 + |p|}{1 - |p|} = \frac{1.925}{.075} = 25.0$$

As can be seen from the calculations above, the E-plane tee works as well as the 3 dB coupler as a protection to the source when only one switch is activated at a time, but the source sees the entire VSWR of 25 when both switches are activated simultaneously. If the source is internally isolated, the E-plane tee would be more economical to use instead of the 3 dB coupler. If the source is not isolated at all, it would be more economical to buy an E-plane tee and an isolator instead of a 3 dB coupler and an isolator.

SECTION 4

SYSTEM INTEGRATION AND CONTROL

4.1 Scope of Section

Presented in this section are the modes of operation, lightning protection, and reserve power for the VPI&SU 17.65 GHz experiment.

4.2 Experimental Control

The VPI&SU 17.65 GHz experiment uses a Raytheon PB-440 computer to control the RF system functions and to acquire data. Various analog methods for collecting data were discussed; but the number of data inputs, the time required for analog to digital conversion for computer programming of data, and the benefits of an on line digital controller convinced project personnel that a digital system of experimental control and data storage was superior to any analog system.[12]

Three RF system data outputs require integration with the PB-440. The two receiver channel output levels range from 0.3 to 2.5 VDC, and the transmitter power meter analog output ranges from 0.0 to 1.0 VDC. The 1.0 VDC represents a full scale deflection of the power meter. If the entire 70 mw of source power is used, the analog output will be 0.7 VDC. These three analog signals are converted to digital form through an eight bit analog to digital converter. The waveguide switches are supplied with 28 VDC at the transmitter, but this 28 VDC is switched electronically by a negative 8 volt logic signal from the PB-440.

The RF system control lines and data lines are rented commercial telephone lines. Rain gauges and wind sensors located along the path are also connected to the PB-440 by these lines. The probability of lightning entering these lines and damaging the solid state circuitry is high, and it has happened on several occasions. Figure 4.1 is a schematic of the filters which were installed at the input of each data and control line. No lightning damage has been reported since the installation of these filters even though several thunderstorms have occurred.

The PB-440 experimental control program operates the transmitter waveguide switches in one of four possible modes which depend upon weather conditions.

Mode 0 is the clear weather operating mode. The +45° channel transmits continuously while the -45° channel is terminated with a matched load. The computer samples both receiver channels every ten seconds and the transmitter power is monitored every one hundred seconds. Mode 1 is the initial rain-induced operating mode. If the cross-polarization changes is dB by 2% or if a rain gauge reports precipitation, the system begins to operate in Mode 1. In Mode 1, the transmitter switches operate plus on-minus off, minus on-plus off, and both plus and minus on. This sequence occurs at four second intervals. The receiver is sampled every one second, and the transmitter power is sampled every four seconds. When the rain rate falls below 6 mm/hr. or if the cross-polarization level becomes stable, the system proceeds to Mode 2. During Mode 2, the transmitter switches every ten seconds, the transmitter power is sampled every ten seconds, and the receiver is

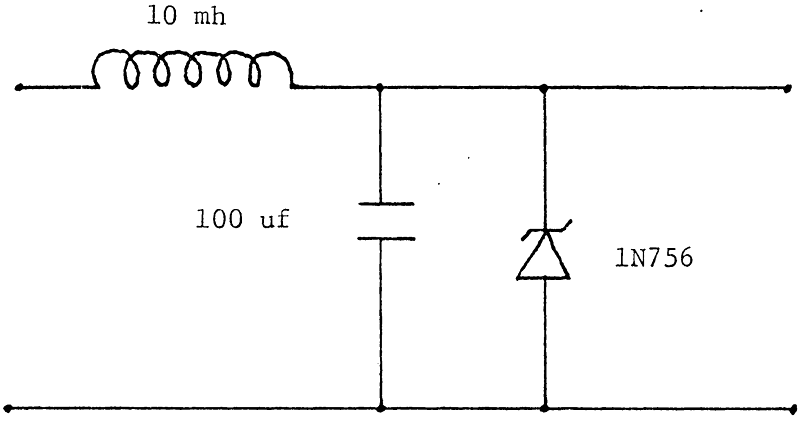


Figure 4.1. Data Line Filter

sampled every two seconds. If the rain rate falls below 3 mm/hr., the system goes into Mode 3. In this mode the transmitter switches every one hundred seconds, the receiver is sampled every ten seconds, and the transmitter power is sampled every one hundred seconds. When the precipitation falls below 2 mm/hr., the system returns to Mode 0 operation. The four modes of operation allow for more efficient use of data storage space.

4.3 Reserve Power

Heavy rainfalls associated with thunderstorms provide excellent depolarization data. Unfortunately, power failures often occur during these same storms. In order to prevent the loss of data due to power failures, the VPI&SU 17.65 GHz RF system is provided with an emergency back up system. A 120 VAC relay monitors the line power. If a line power failure occurs, the relay switches in the emergency power which consists of a battery bank and voltage regulators. The battery bank is also provided with a trickle charger. One pole of each emergency power relay is reserved for an alarm signal to the PB-440.

Although the need for the emergency power has not yet occurred, the receiver and transmitter have been bench tested during the emergency power system. Both the receiver and transmitter remained in proper calibration after the change over.

SECTION 5

EVALUATION OF DATA

5.1 Scope of Section

Presented in this section are the methods for extracting the attenuation and cross-polarization values from the detector outputs. Sample cross-polarization data are also presented.

5.2 Data Interpretation

Data conversion is accomplished by linear interpolation using the calibration curves stored in the BB 440. The linear transfer function of the receiver requires that only two points on the curve be defined, but each curve contains 32 points which are updated after every recalibration.

Cross-polarization calculations must precede any attenuation measurements because the cross-polarized received signal is lumped with attenuation. Figure 5.1 represents the three-mode sequence of the transmitter. Below is an example of how data are extrapolated from the receiver. The clear weather received signal is 2.5 VDC per channel. The received signals below 2.5 VDC occur during rain. The slope of the receiver transfer function is 34 dB/volt.

Position 1: plus channel on - minus channel off

$R^+ = 2.3$ VDC

$R^- = 1.2$ VDC

XPOL (dB) = $-1.1(34) = -37.4$ dB

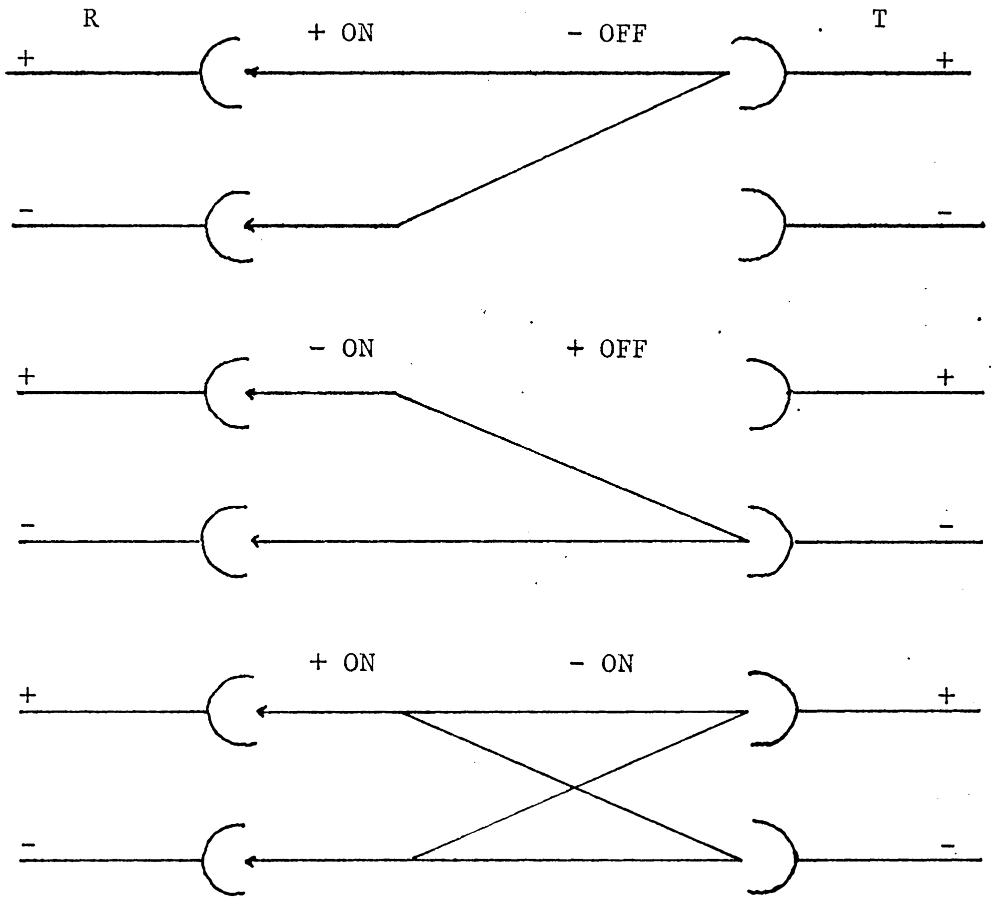


Figure 5.1. 3 Mode Sequence

Position 2: plus channel off - minus channel on

$R^+ = 2.3$ VDC

$R^- = 1.2$ VDC

XPOL (dB) = -37.4 dB

Position 3: plus channel on - minus channel

$R^+ = 2.4$ VDC

$R^- = 2.4$ VDC

From the above values of R^+ and R^- it can be seen that each channel has a cross-polarization contribution of 0.1 VDC. The apparent 0.2 VDC attenuation value must then be corrected by 0.1 VDC.

$A^+ \equiv$ plus channel attenuation $= 2.5-2.3+0.1 = 0.1$ VDC

$A^- \equiv$ minus channel attenuation $= 2.5-2.3+0.1 = 0.1$ VDC

$A^+ = 3.4$ dB

$A^- = 3.4$ dB

5.3 Sample Data

Tipping bucket rain gauges along the path provide rain rate information for the PB-440. All this information is timed so that curves of rain rate vs cross-polarization may be plotted. Figure 5.2 is a plot of cross-polarization vs rain rate for the storms of 1972 for which the VPI&SU 17.65 GHz system was operational.

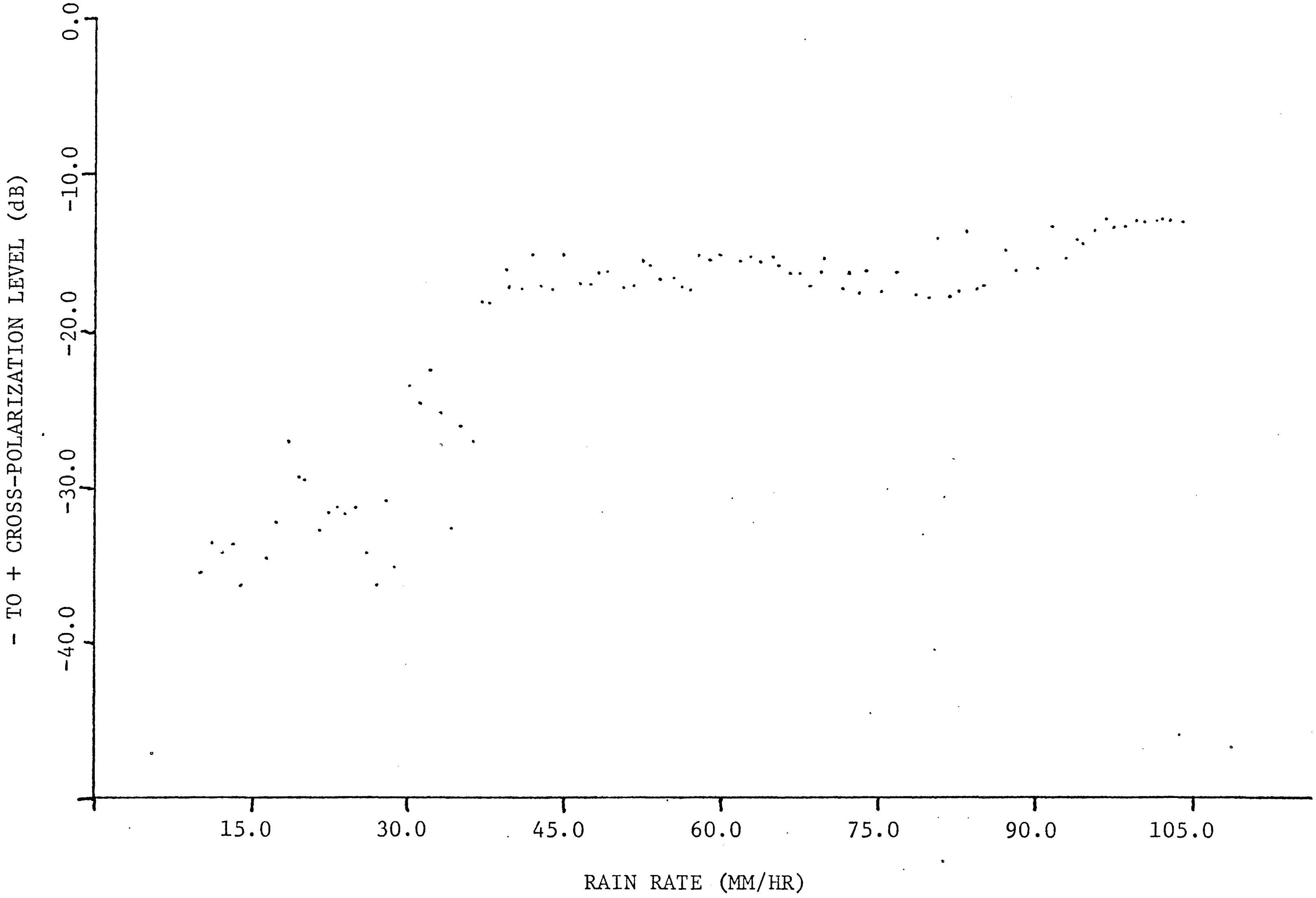


Figure 5.2. Sample Cross-Polarization Data

SECTION 6

CONCLUSIONS

Rain-induced attenuation and depolatization can be observed and measured with an RF system fabricated from commercially available millimeter wavelength components. Path length, dynamic range, and polarization isolation are the three specifications that must be defined and met before attenuation and depolarization data can be acquired for a wide range of rainfall rates.

SUMMARY

Rain-induced depolarization is a limiting factor in the use of polarization diversity as a method for increasing millimeter wave channel capacity. Significant data on rain-induced depolarization could be obtained if an RF system that could measure depolarization was available. An introduction concerning RF system path length is followed by the RF system design. The thesis concludes with sample data taken with the V. P. I. & S. U. RF system.

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AN RF SYSTEM FOR MILLIMETER WAVE PROPAGATION EXPERIMENTS

by

Robert E. Marshall

ABSTRACT

This thesis describes a method for designing an RF system for measuring rain-induced attenuation and depolarization at millimeter wavelengths. Path length, dynamic range, and polarization isolation are discussed with respect to their importance to RF system performance.

Design considerations for the VPI&SU 17.65GHz,CW, RF system are presented. The path length is 1.43km, the receiver dynamic range is 71dB, and the orthogonal polarization isolation is greater than 60dB for the receiver and transmitter.

The paper concludes with sample data taken with the VPI&SU system during several rain storms in 1972.