Short Hop Radio System Experiment

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This paper reports a two-hop system experiment, designed to demonstrate the viability of the concept described in previous papers. A single RF channel, instrumented in the 11 GHz common carrier band, is transmitted from a terminal to a repeater one and a half miles away. After passing through the repeater, the signal is transmitted back to the terminal. We discuss the system parameters in relation to the requirements of operation at frequencies above 10 GHz; we also describe design, construction, and performance, as well as the lessons learned from one year of operation.

I. INTRODUCTION

Because the ever-increasing need for more communications circuits is crowding the frequency spectrum below 10 GHz, it is imperative to study the problems associated with microwave radio systems at frequencies above 10 GHz. The problems involved in the use of these frequencies and the resulting system concepts and constraints are discussed in a companion paper.[1] To bring these system concepts closer to reality and to find out whether the associated hardware is practical in the light of present technology, an experimental radio line has been built which embodies many of the essential system concepts. This paper describes the experimental system and its relation to the fundamental system concepts.

The experimental system is a research experiment on a system level and not a developmental radio system. Consequently many circuits and measurements necessary for a developmental system, such as order wire, alarm circuits, detailed cross modulation, and thermal noise measurements, were not made. Rather, efforts were confined to the more basic and unproven aspects of the radio line part of the system concept.

II. GENERAL

2.1 *Rain Attenuation and System Design*

The main consideration in designing radio systems operating at frequencies above 10 GHz is the attenuation caused by rainfall. During a uniform rainfall of four inches per hour the rain attenuation in the 11 GHz common carrier band is 6 dB per mile.[1] At higher frequencies the attenuation increases sharply; at 18 and 30 GHz the attenuations are 15 and 30 dB per mile, respectively. Such heavy rain occurs infrequently, but to achieve the reliability required of common carrier service, radio systems must be designed so that such losses do not cause excessive system outages.

An important system constraint follows immediately from the magnitude and nature of rain attenuation: *The repeater path length must be short compared with the path lengths used at lower frequencies.* Since the rain attenuation increases in decibels per mile, the path length cannot be extended by the brute force method of increasing the transmitter power. For example, with a 30 GHz system designed to work through a uniform rainfall rate of four inches per hour, an increase in path length of one mile would require a thousand-fold increase in transmitter power.

Many fundamental system characteristics follow directly from the requirements of closely spaced repeaters. These are shown in Fig. 1 which illustrates the necessary and desirable characteristics of a viable radio system operating at frequencies above 10 GHz.

The concept of an attractive low cost tower with no building, and located on a public right-of-way, reflects a fundamental change in the philosophy of radio system design whereby tower and site performance is relaxed in favor of more adaptable and higher performance electronics. One approach is to house the entire repeater in a small enclosure on top of a metal pole which is just strong enough to keep the receiving antenna within the beam width in the strongest wind. With the repeater at the top of the pole, the need for a building and for long waveguide runs is eliminated, keeping right-of-way requirements to a minimum. The electronics must be extremely reliable, maintenance free, and able to operate in the outdoor environment. Since a system has many repeaters, there will be many interference exposures, and an interference resistant modulation method is needed requiring a broadband channel.[2] Figure 2 is a block diagram of a one-way repeater; a repeater layout, using a two frequency plan and two polarizations, is illustrated in Fig. 3.

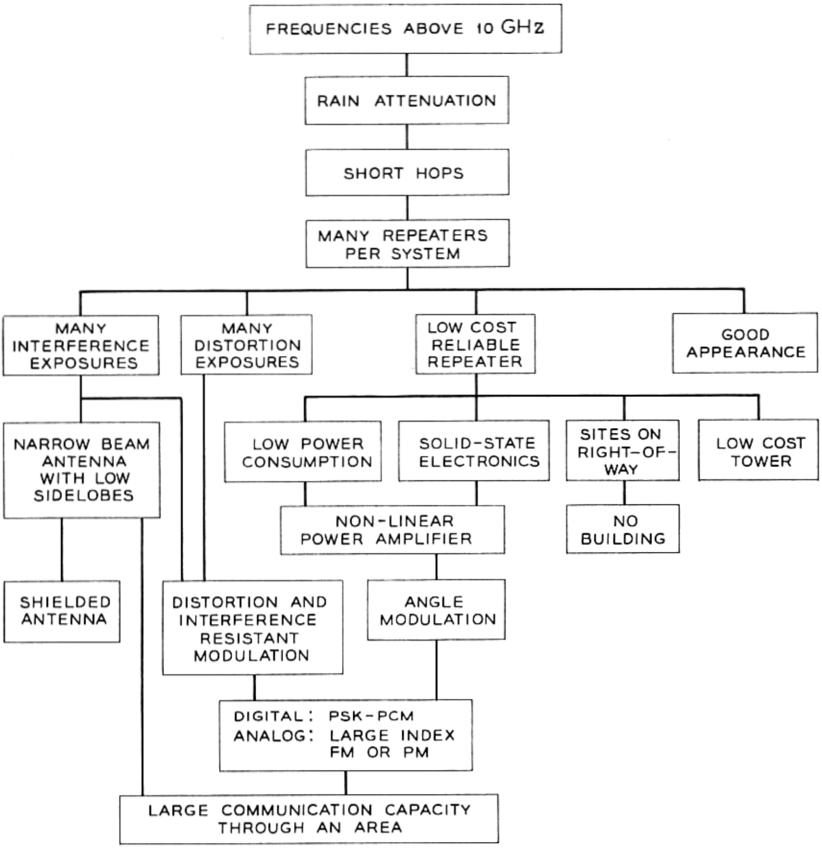


Fig. 1 — Characteristics of radio systems operating at frequencies above 10 GHz.

Illustrative parameters of an 11 GHz system of this type are summarized in Table I. The most significant parameters are: the short path length because of rain attenuation; the relatively low transmitted power, a consequence of the solid state and lower power consumption requirements; the receiver noise figure, required because of the fade margin and low transmitted power; the low dc power consumption; the bandwidth, which follows from the requirement of interference resistant modulation; and the intermediate frequency.

The gain of the varactor upconverter power amplifier is one of the main considerations in the selection of the system intermediate frequency. A low intermediate frequency favors low power consumption and increases the gain of the upconverter power amplifier. The

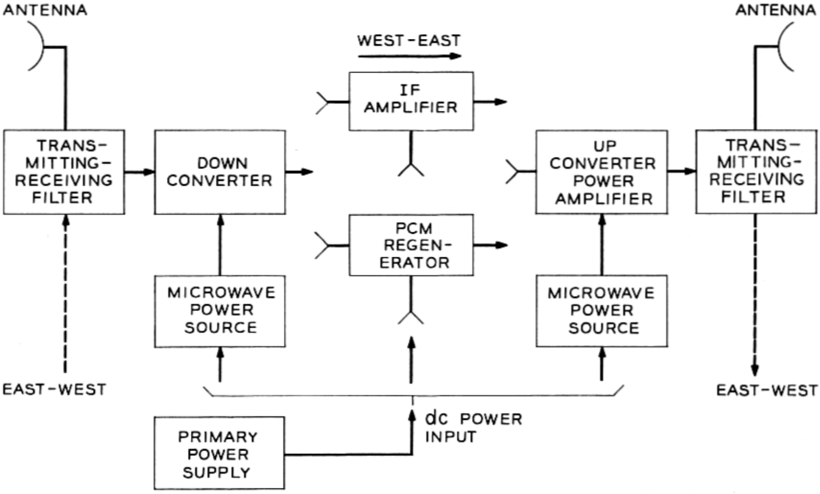


Fig. 2 — Block diagram of a one-way repeater.

300 MHz intermediate frequency chosen for this application is low enough to achieve substantial power gain and is still sufficiently high to obtain the desired 120 MHz IF bandwidth. To obtain an RF channel bandwidth of 120 MHz, a 1 dB bandwidth of at least 120 MHz is required for the upconverter, downconverter, and IF amplifier.

2.2 *Purpose of System Experiment*

Because of the new concepts and the device requirements involved, it is necessary to perform a system experiment to demonstrate that such a system can be realized. Accordingly, the system experiment described in this paper was performed to demonstrate that:

(*i*) The necessary devices, circuits, and hardware can be built,

(*ii*) Satisfactory operation in outside weather conditions is possible,

(*iii*) It is possible to operate a repeater on a few watts of dc power from a thermoelectric generator,

(*iv*) A pole mounted solid state repeater can be reliable and have long life,

(*v*) The appearance of a pole mounted repeater is acceptable,

(*vi*) And to reveal unforeseen problems.

2.3 *General Description of the Experimental System*

The experimental system has as many of the characteristics of a complete system as practical. It was not necessary to duplicate all the transmitters and receivers and we decided that the channel combining networks need not be designed. Consequently, for the experiment, the repeater configuration shown in Fig. 3 was simplified to that shown in Fig. 4. However, the repeater housing was designed to accommodate a complete repeater consisting of four transmitters, four receivers, channel combining networks, and two power supplies; the units used were designed in the same plug-in form and size as would be required in a complete repeater. The tower was designed to meet the wind load and weight requirements of a complete repeater.

The radio system experiment is illustrated by Fig. 5. It consists of a terminal transmitter and receiver on Crawford Hill and a single channel repeater near the Holmdel laboratory 1.5 miles away. At each location a receiver, transmitter, dc-dc converter-regulator, and an antenna are housed inside a cylinder at the top of a 60-foot aluminum pole. A second, empty housing is mounted on the Holmdel pole to simulate a complete repeater. Propane gas for the thermoelectric

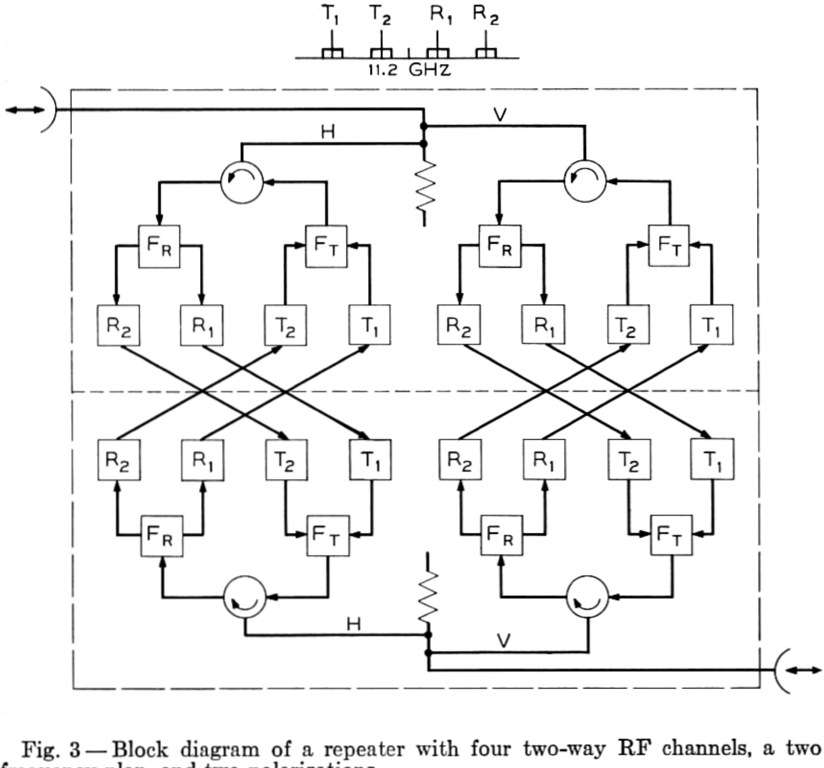


Fig. 3 — Block diagram of a repeater with four two-way RF channels, a two frequency plan, and two polarizations.

TABLE I—ILLUSTRATIVE REPEATER PARAMETERS FOR AN 11 GHz SHORT HOP RADIO SYSTEM

Radio frequency	10.7 to 11.7 GHz
Transmitted power	+14 dBm
Antenna diameter	2.5 feet
Antenna beamwidth	2.5 degrees
Antenna gain (antenna efficiency = 0.5)	36 dB
Path length	3 miles
Section loss	54 dB
Received signal power	−40 dBm
Fading margin (6 inches per hour uniform rate)	30 dB
Receiver noise figure	7 dB
Intermediate frequency	300 MHz
IF bandwidth	120 MHz
Width of base band	4.5 MHz
Approximate voice circuit capacity per RF channel	1000 channels
dc power consumption per 2-way RF channel	10 W

generator, mounted near the bottom of the pole, is kept in two underground tanks. At Crawford Hill, a building near the pole is used as a terminal building for test purposes. The Holmdel site has no building or commercial power; it is an isolated repeater. At the terminal the IF signals are connected to the test equipment through 100-foot coaxial cables which run down the inside of the pole and underground into the

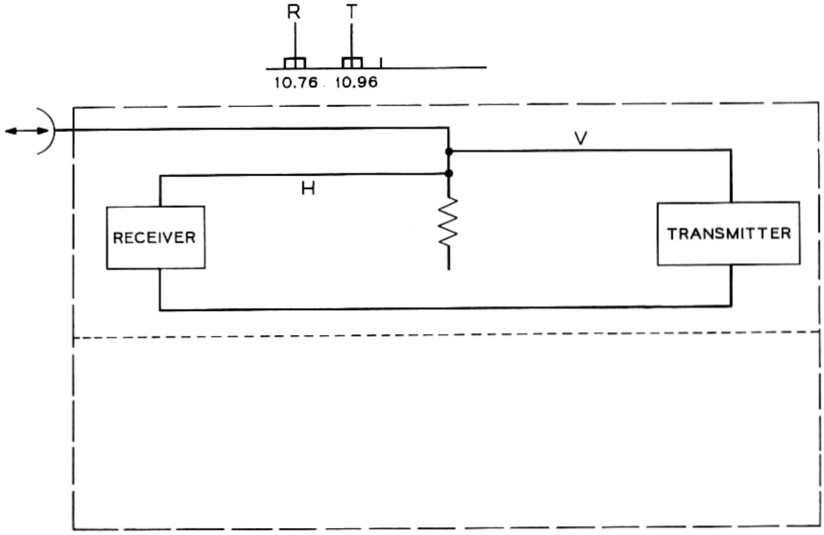


Fig. 4—Block diagram of the experimental system repeater.

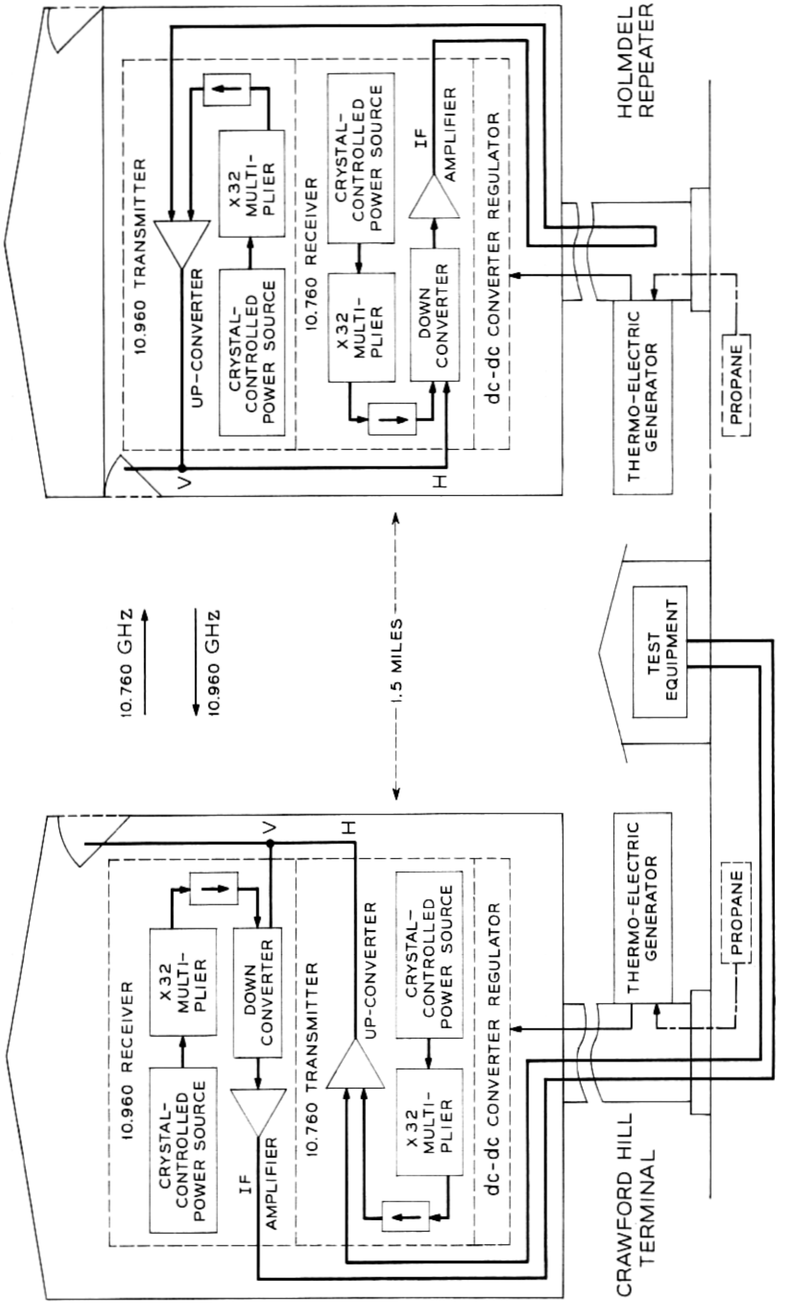


Fig. 5 — Pictorial block diagram of the system experiment.

building. At the Holmdel repeater, the IF connection is made at the bottom of the pole for test purposes; normally the connection would be made at the top of the pole running only from one housing to the other. The Crawford Hill to Holmdel transmission is horizontally polarized and the return transmission is vertically polarized.

To check the operation of the system, the transmitter power, receiver AGC voltage, dc supply voltages, and thermoelectric generator power, can be monitored at both terminal and repeater. At the terminal, temperature sensors monitor the hottest points in the power supply, transmitter, and receiver, and the inside and outside ambient temperatures.

Satisfactory operation from −40°F to +135°F was set as a system objective. This was chosen as being approximately the range of temperatures common within the contiguous United States. In field use, no one repeater would normally encounter such a wide range. Because of a stability problem at the interface between the driver and X32 multiplier chain in the microwave power sources, the range actually achieved was −30°F to +125°F although all other circuits met or exceeded the original objective. This problem has subsequently been solved and microwave power sources suitable for use in the system have operated over the −40°F to +135°F temperature range.

III. REPEATER ELECTRONICS

3.1 *Basic Circuits*

3.1.1 *The dc Power Circuits*

The dc power circuits generate the required voltages from a propane gas thermoelectric generator, and provide both source and load regulation. Figure 6 shows the circuits and power levels required for a one-way repeater.

Electrical power is generated by a thermoelectric generator rated at 28 watts minimum at 75°F. Because of the increase in cold junction temperature with the ambient temperature, the output power decreases as the outside temperature increases. The generator power rating was chosen so that system requirements would just be met at the highest temperature of +140°F. At the fuel consumption rate of one gallon per day, operation for two thirds of a year without refueling is possible with two 120 gallon tanks.

The converter-limiter is a component of the thermoelectric generator which converts the 4 volt generator voltage to approximately 26.5

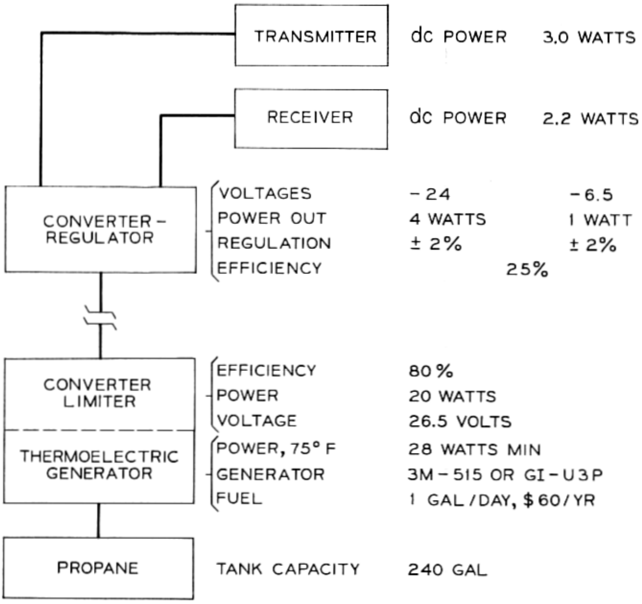


Fig. 6 — The dc power circuits and power levels.

volts, a more useful value for transistors and distribution circuits, and limits the converter voltage to that value if the load is reduced. The limiter also provides some regulation of converter and generator power changes.

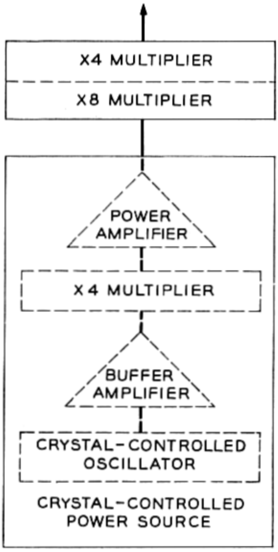
The converter-regulator, also a commercial unit, is located in the repeater housing and supplies -24 volts regulated against load and supply variations. The -6.5 volts is derived from the -24 volts by use of a regulator diode. Both voltages are regulated to less than ± 2 percent for combined load changes, input power changes, and temperature variations.

A total power of 5.2 watts is used for one transmitter and one receiver. Thus dc power requirements are approximately 10 watts per two-way RF channel. The overall dc conversion efficiency is only 20 percent because of the use of two commercially available converters and the method of deriving the -6.5 volts. A power converter has been reported which uses a variable pulse width technique to regulate against input voltage changes and provides series regulators to regulate against load changes; efficiencies as high as 69 percent were obtained.[3] This technique of combining series regulators with preregulation appears well suited for this application where the converter can transform the thermoelectric generator voltage to the several output voltages required for the system and regulate against generator power variations. The voltages can be transmitted to series regulators located at the radio package to regulate against load changes. Overall efficiencies of 60 to 70 percent should be obtained since the power levels are about 25 watts. Assuming 10 watts per two-way channel and 50 percent converter efficiency, an 80 watt thermoelectric generator would be required for the complete repeater in Fig. 3.

3.1.2 *Microwave Power Sources*

The microwave power sources generate the microwave power required to pump the varactor upconverters and the Schottky-barrier diode downconverters. Figure 7 is a block diagram of a power source and typical results for transmitter and receiver sources.

The microwave power source consists of a 327 MHz crystal-controlled power source followed by a X32 multiplier chain. The frequency stability is set by the crystal controlled oscillator and is well within the ±0.005 percent requirements over the temperature range. The power amplifier is operated class C for maximum efficiency since



	TRANSMITTER	RECEIVER
OUTPUT FREQUENCY	10.460 GHz	10.660 GHz
OUTPUT POWER	19.7 dBm	9.8 dBm
RF EFFICIENCY	8.0 dB	10.3 dB
OUTPUT FREQUENCY	326.875	333.125 MHz
OUTPUT POWER	27.7 dBm	20.0 dBm
dc POWER	2.36 WATTS	1.15 WATTS
EFFICIENCY	25%	9%
	OVERALL	
EFFICIENCY	4%	0.8%
TEMPERATURE RANGE	−30°F TO +125°F	
STABILITY	0.005%	

Fig. 7 — Microwave power source.

it is at the highest power level in the chain. A X8 varactor multiplier connected directly to a X4 multiplier converts the 327 MHz to the required 10.460 GHz. The overall efficiency of the high power microwave source is 4 percent.

Since the transmitter microwave power source uses almost half of the dc power required for a one-way channel, it was designed for maximum efficiency subject to the constraints of environmental stability and reliable starting. For this experiment the receiver source consists of a high power unit adjusted for the reduced power required by the receiver. A separate design of the low power source would result in efficiencies at least as good as obtained with the high power source.

In accordance with previously established system concepts, the microwave power source must be efficient, reasonably simple, and compact—attributes which tend toward low cost. Consequently, very efficient circuits with high order multiplication and no isolators were used. However, isolators are commonly used to solve the stability and starting problems inherent in nonlinear circuits; both of which are aggravated by efficient circuits and temperature and voltage variations. Therefore the design of a chain without isolators and their obvious disadvantages required theoretical and practical solutions to the problems of stability and starting.

Stability criteria for high order varactor multipliers have been established by Dragone and Prabhu.[4,5] With the aid of these criteria the X32 chain was successfully designed and built without the use of isolators. In the connection of the crystal controlled power source to the X32 chain the same instability mechanism was encountered because of the nonlinear class C power amplifier and X4 multiplier in the crystal controlled power source. It can easily be demonstrated that phase modulation is propagated in both directions through the class C power amplifier and thus through the first X4 multiplier. Therefore, the total instability feedback path includes a phase modulation gain of 128 and the round-trip phase gain of the power amplifier which can be large.

In the microwave sources actually used in the system these stability problems limited the temperature range to −30°F to +125°F. Subsequently, procedures for power amplifier design and adjustment have been found which insure that the amplifier round trip phase gain is less than unity and that the amplifier supplies sufficient power into the varactor multiplier at all power levels to insure reliable starting. Microwave power sources, similar to those used in the system, have operated over the temperature range of −40° to +135°F with a small penalty in efficiency.

3.1.3 *Receiving Downconverter*

The receiving downconverter converts the low level received microwave signal to the intermediate frequency with a minimum of noise degradation and sufficient gain to reduce the effect of the main IF amplifier noise. The downconverter is an image rejection balanced mixer using Schottky-barrier diodes, followed by an integrally connected low noise preamplifier.[6]

The combination of intermediate frequency, bandwidth, and noise figure, with the other system constraints, require extending downconverter performance beyond existing technology. An average noise figure of 5.6 dB was obtained; Table II summarizes the results.

3.1.4 *IF Amplifier*

The IF amplifier provides most of the repeater gain and the automatic gain control necessary to maintain a constant transmitted power. This is accomplished with three low level variable-gain stages and three high level fixed-gain stages.[7,8]

The amplifier has a 1 dB bandwidth of 120 MHz. With a normal input signal level, the gain is 33 dB with an output power of +7.5 dBm into 50 ohms with 1 dB gain compression. The automatic gain control keeps the output power constant over a 43 dB range in the input level.

Most of the gain and all of the gain control is accomplished in the low level section to minimize the total power consumption and noise figure. The total dc power consumption is 0.65 watt. With 33

TABLE II—SUMMARY OF DOWNCONVERTER PERFORMANCE

Radio signal frequency	10.760 GHz
RF signal power (normal)	−40 dBm
Pump frequency	10.460 GHz
Pump power (for 2 diodes)	+9.8 dBm
Intermediate frequency	300 MHz
IF power	−21.4 dBm
RF to IF gain	18.6 dB
Frequency response	flat ± 0.1 dB, 240 to 350 MHz 0.3 dB down at 230, 360 MHz
Noise figure, 75°F	5.3 dB at 300 MHz 5.6 dB average, 240 to 360 MHz
Preamplifier noise figure	2.0 dB
Temperature range	−40 to +140°F

dB gain the noise figure is 13.6 dB, contributing only 0.4 dB to the receiver noise figure.

3.1.5 *Varactor Upconverter Power Amplifier*

The varactor upconverter power amplifier converts the 300 MHz IF signal from the main IF amplifier to the 11 GHz RF band with sufficient power for transmission over the radio path. It consists of a varactor diode mounted across the waveguide, an integrally attached IF amplifier, and two waveguide filters which provide the proper reactive terminations.[9]

Basic considerations in the design of the upconverter are the bandwidth and the pump efficiency. The bandwidth was obtained by mismatching the interface between the amplifier and the varactor diode in an optimum way. The upconverter was designed for maximum pump efficiency in order to get the maximum output power possible with the available pump power.

The bandwidth obtained was slightly less than the desired 120 MHz between 1 dB points because of a slight asymmetry. The output power is typically 16.2 dBm with a pump power of 20 dBm; the IF to RF gain is 13.2 dB, including the amplifier, when the amplifier input power is +3 dBm.

3.2 *Receiver*

The receiver consists of a low power microwave power source, a downconverter, and a main IF amplifier as shown in Fig. 5. An isolator is required between the output of the microwave power source and the narrowband pump input filter of the downconveter to satisfy the stability criteria for multiplier chains.[4,5] The output of the preamplifier is connected to the input of the main IF amplifier through a very short connection, easing the output return loss requirement on the preamplifier.

Since the available transmission path is approximately one-half of the nominal design length of 3 miles, a 6 dB pad was added at the receiver input to simulate the additional 1.5 miles. The actual downconverter gain is 4 dB more than the design value; so rather than operate the variolossers at their limit, a 4 dB pad was added to the main IF amplifier input. With these adjustments, typical receiver power levels are: received power at the down converter, −40.2 dBm; IF power out of the down converter, −21.6 dBm; IF power out of the main IF amplifier, +7.5 dBm. The power out of the microwave source, less 0.4 dB isolator loss, is 9.4 dBm at the local oscillator port of the down converter. Using the 300 MHz, 75°F, spot noise figures of 5.3 dB for the down converter and 13.6 dB for the main IF amplifier, and the 18.6 dB gain of the down converter, the overall receiver spot noise figure is 5.7 dB. The addition of the 4 dB pad degrades the noise figure to 6.2 dB.

The transmission frequency response of the complete receiver is shown in Fig. 8 for temperatures of +140°F, +75°F, and −40°F and at each temperature for input power levels in the range of −40 to

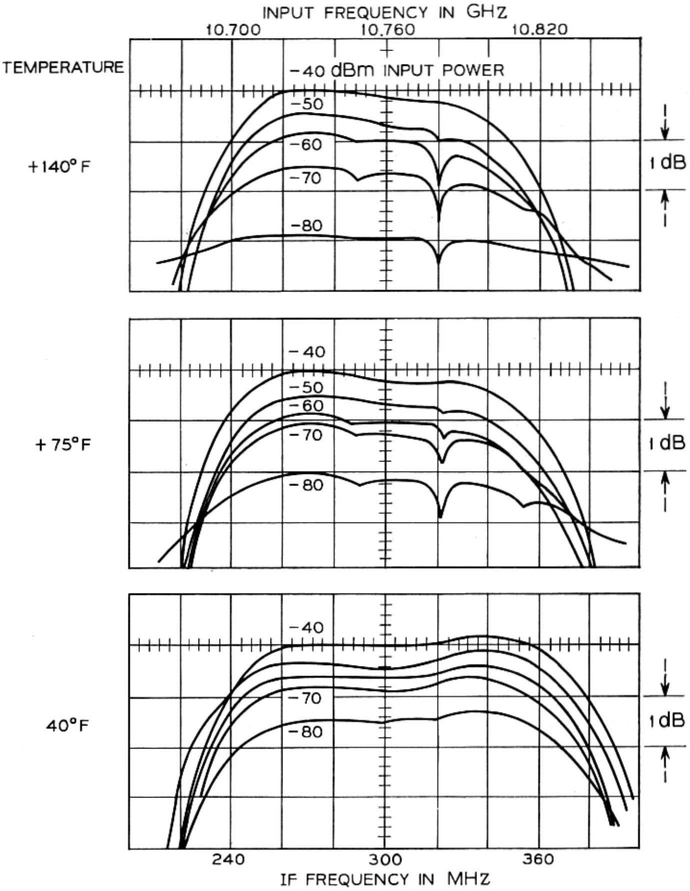


Fig. 8 — Frequency response of a complete receiver at +140°F, +75°F, and −40°F, and −40 to −80 dBm input power levels.

−80 dBm. At 75°F and −40 dBm input level, the response is down 1 dB at 240 and 360 MHz, but has a small slope across the band. At +140°F the slope increases causing the response to be down 1.8 dB at 360 MHz; at −40°F the slope is reversed causing the response to be 0 dB down at 360 MHz. These response variations are basically those of the main IF amplifier with some change resulting from changes in pump power into the down converter. The dip in the response at about 320 MHz is caused by an interfering tone which is the 33rd harmonic of the 327 MHz power source present at the output of the X32 multiplier chain. Its equivalent input level is −87 dBm and is a function of the selectivity of the down converter pump input filter.

Figure 9 shows the 10.960 GHz receiver. The entire receiver is mounted on a 12 × 12 × 2.5-inch aluminum frame and weighs 14.3 pounds. This layout is designed to allow installation or replacement by simply plugging in the unit. Waveguide alignment is assured by using a short piece of flexible waveguide with alignment pins. Choke joints with metalized gaskets are used to prevent leakage.

The crystal-controlled power source is insulated to conserve the heat generated within the box and reduce the effects of high relative humidity. For example, if the outside air is saturated at 80°F, an 8°F increase in temperature reduces the relative humidity inside the box to about 70 percent.

3.3 *Transmitter*

The transmitter contains a high power microwave power source and a varactor upconverter power amplifier connected through an isolator. The output of the IF amplifier in a repeater or the terminal equipment is applied to the IF input of the upconverter at a +3 dBm level. The 19.7 dBm out of the microwave power source, less 0.4 dB isolator loss, gives 19.3 dBm of pump power at the upconverter, for which the output power is about 15.5 dBm. The frequency response of the transmitter is the same as that of the upconverter.

Figure 10 shows the 10.760 GHz transmitter. The transmitter weighs 12 pounds and is mounted on the same type of aluminum frame as the receiver. The flexible waveguide used for waveguide alignment and the dc power plug are on the right side of the unit.

3.4 *Antenna*

The antenna consists of a small aperture feed, a focussing paraboloidal reflector, and a plane reflector in an inverted periscope ar-

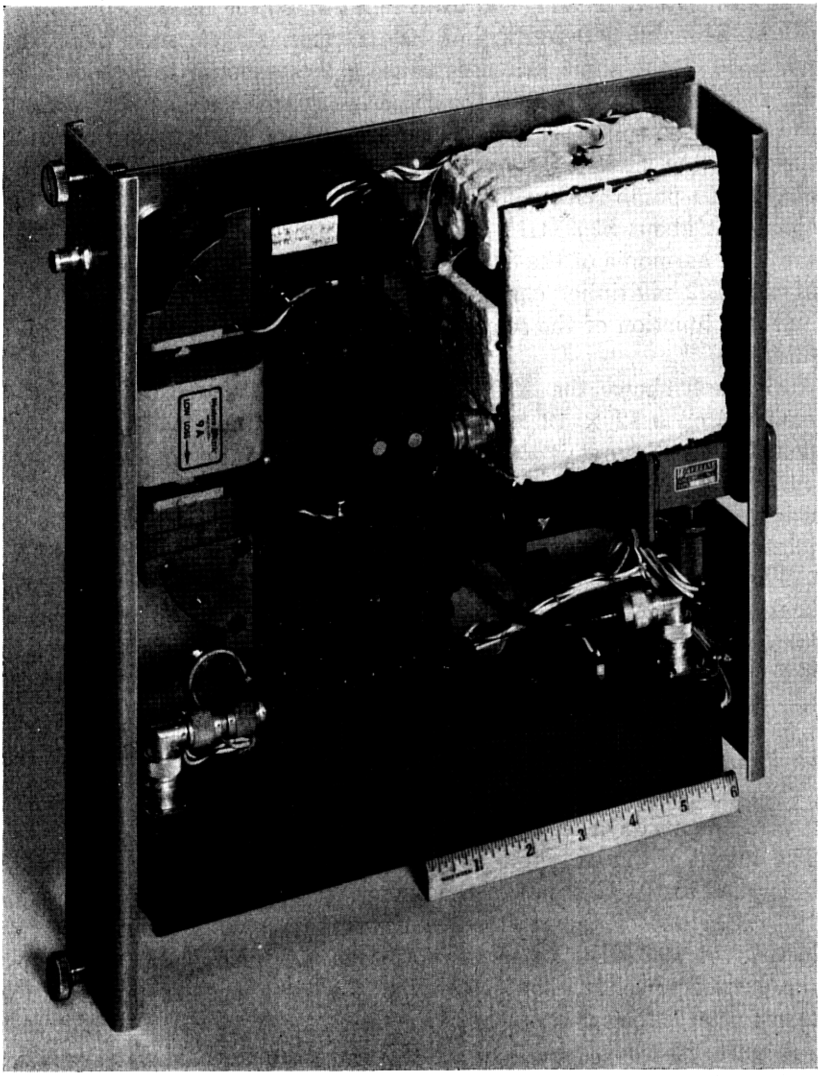


Fig. 9 — The 10.960 GHz receiver.

rangement. The axis of the feed and parabola coincide with the axis of the housing which supports and shields the radiating elements. Thus the packaged antenna has the highly desirable low side lobe and rear lobe radiation characteristics necessary for radio interference suppression.

The important characteristics of the antenna are listed in Table III and extensive measurements are reported in a companion paper.[10] Of particular importance are the return loss and cross polarization coupling loss because they determine the amount of filtering required to isolate adjacent and cross polarized channels and thereby affect system channel capacity.

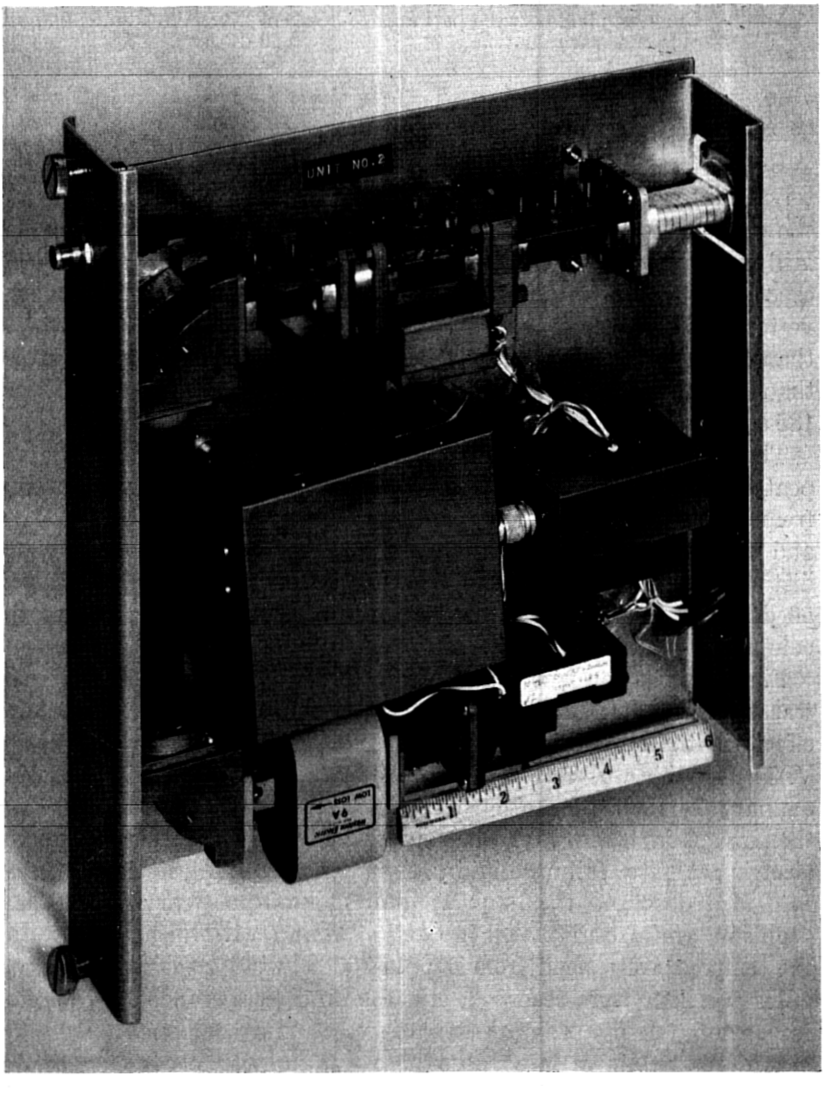


Fig. 10 — The 10.760 GHz transmitter.

TABLE III—MAJOR CHARACTERISTICS OF THE ANTENNA WITH WEATHER COVER

Aperture diameter	2.5 feet
Beamwidth, 3 dB	2.4 degrees
Gain (57% aperture efficiency)	36.6 dB
Return loss (10.7 – 11.7 GHz)	>18 dB
Cross polarization coupling	>35 dB
Cross coupling between packages	>75 dB
Side and rear radiation	>60 dB for > 120°

3.5 *System Measurements and Performance*

Before final field installation, the receiver, transmitter, and converter-regulator were tested in the laboratory as an IF repeater. Figure 11 shows the RF-to-RF transmission frequency response of the Crawford Hill repeater at +140°F, +76°F, and −40°F. The band shape, especially the fine grain structure, is caused by the varactor upconverter. In-band ripples are less than 0.4 dB; the response is down less than 1.5 dB at the band edges. The usable bandwidth is much larger than 120 MHz; for example, the 3 and 6 dB bandwidths at 75°F are 185 and 220 MHz, respectively.

The distortion resulting from the amplitude response of the repeater transfer function has been computed for large index analog frequency modulation.[11] For a noise modulation bandwidth of 5 MHz, and an rms frequency deviation of 15 MHz, the computed signal-to-distortion ratio at the highest baseband frequency is approximately 56 dB. The room temperature response of Fig. 11 was used for the computation and a linear phase response was assumed.

Field installation was completed in mid-November 1967; operation was intermittent at first. The trouble, which was traced to humidity effects in the crystal-controlled power source, is discussed in Section V. The trouble was corrected and the system was placed in operation January 2, 1968. The electronics have operated continuously since then except for a few days when the system was off because of thermoelectric generator failures and in July when a lightning stroke on Crawford Hill damaged the main IF amplifier output transistors. These problems are also discussed in Section V and VI. During this period the temperature ranged from 0°F to 100°F, wind gusts as high as 65 miles per hour were recorded, and the humidity averaged 99 percent for as long as five days. When the electronic components were removed for repair in late July, there was no visible evidence of deterioration or corrosion and there was no deterioration of performance.

IV. REPEATER MECHANICS

4.1 *Repeater Housing*

The repeater housing is a weatherproof but well ventilated shelter for the repeater electronics and the antenna. It is a cylindrical aluminum canister 34 inches in diameter and 42 inches high. About half of the volume is used for the inverted periscope antenna which was designed for such applications. Figure 12 shows the antenna side of the housing. The volume under the plane reflector is sufficiently large

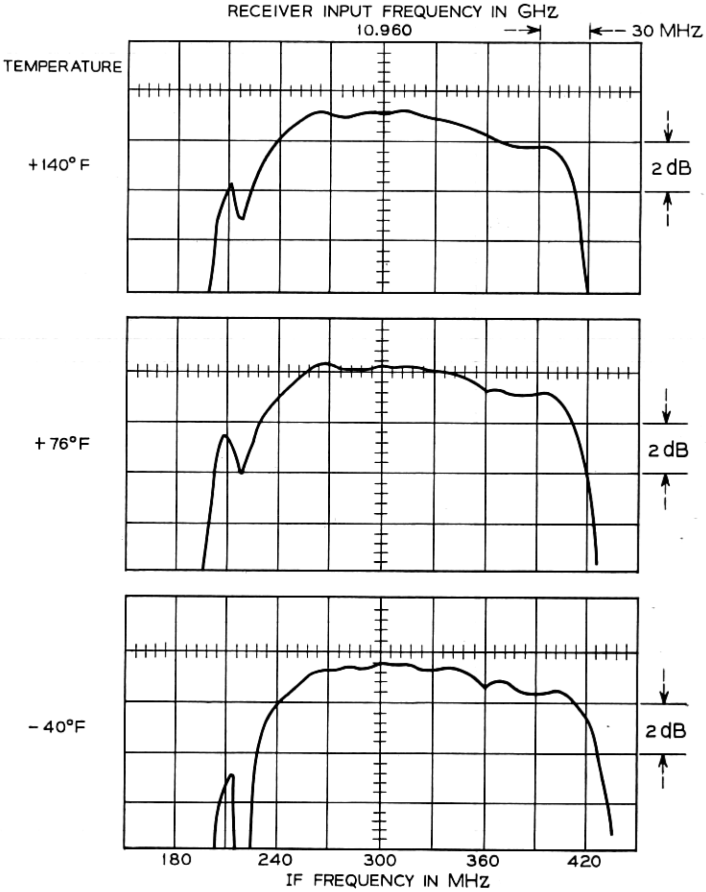


Fig. 11 — RF-to-RF transmission frequency response of the Crawford Hill repeater measured in the laboratory.

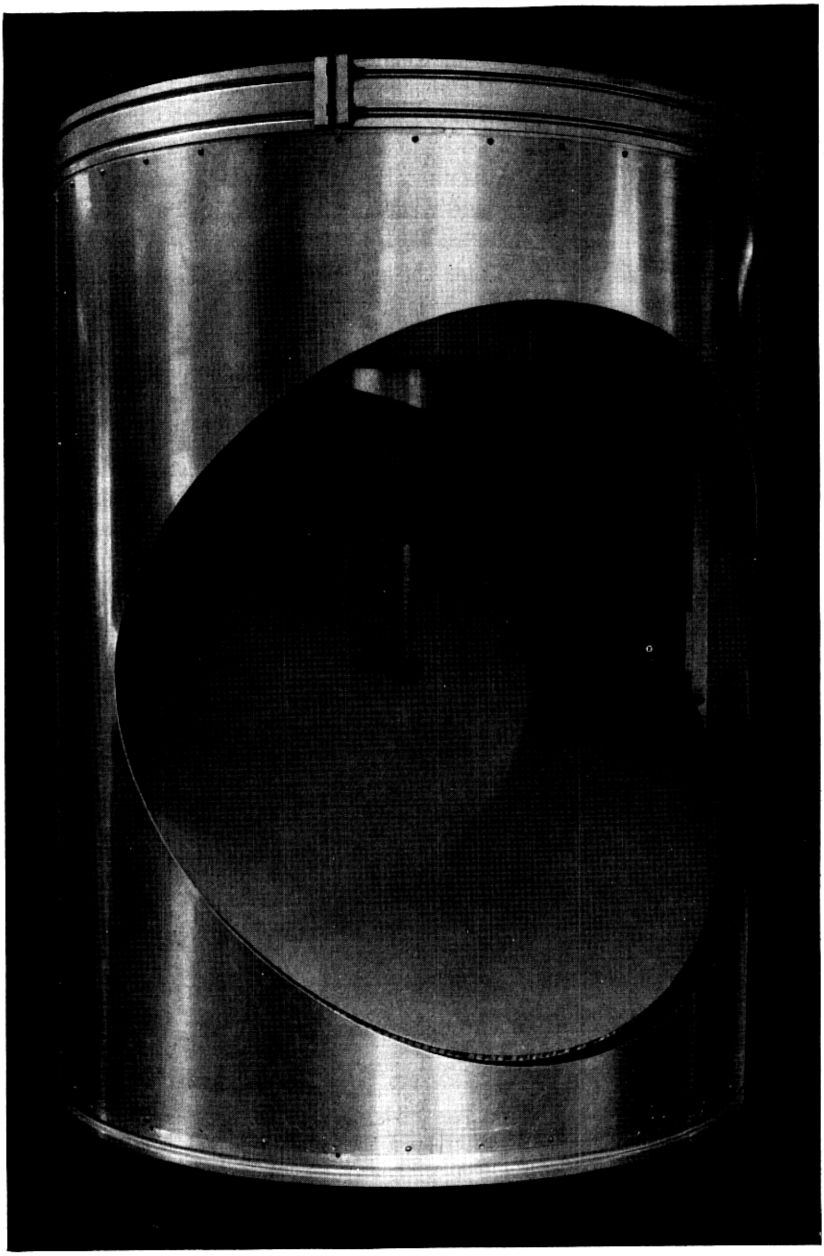


Fig. 12 — Repeater housing and antenna with weather cover removed.

for the four transmitters, four receivers, channel combining networks, and two power supplies of the system configuration of Fig. 3. Figure 13 shows the electronics side of the housing with access covers removed and four model plug-in units for the horizontally polarized channels installed. The channel combining networks are between the rear of the plug-in units and the back panel. The two power supply chassis fit in the shorter slots toward the outside of the housing.

Also visible in Figure 13 are the vent holes in the bottom of the housing; the larger hole in the center is used for IF interconnection cables between canisters. The canisters are attached to each other and to the mast by a grooved band which fits matching grooves on the top and bottom of each housing and on the mast flange. This permits azimuth alignment by rotating the entire housing. Elevation beam alignment is accomplished by tilting the antenna plane reflector; an elevation position indicator and vernier adjustment is located on the outside of the housing above the access covers. This method of alignment does not require movement of the electronics, antenna feed, or parabola and is one of the attractive features of the inverted periscope antenna.

Based on a wind loading area equal to two thirds of the projected area of the housing and a 100 miles per hour wind pressure of 40 pounds per square inch, the total wind load for each housing is approximately 300 pounds, or 600 pounds for a complete repeater. The weight of the housing and antenna without electronics is about 85 pounds which, using the previously mentioned weights for the plug-in units, gives a weight of about 200 pounds per housing or 400 pounds for a completely equipped repeater.

4.2 *Repeater Tower and Foundation*

The short repeater spacing allows the use of towers which need only be tall enough to clear the trees. Spun aluminum poles are ideally suited for this application for the following reasons: (*i*) they have an attractive and commonly accepted appearance, (*ii*) aluminum remains clean and attractive with no maintenance in contrast with non-stainless steels, an important consideration since repeaters will be located on public rights-of-way, (*iii*) spun aluminum poles are readily available because of their many other uses, and (*iv*) aluminum is cheaper than stainless steel for the same stiffness. A tapered pole is used because it has a more pleasing appearance and because truncated hollow cones generally are more efficient load carrying structures than cylindrical tubing in column and end-loading applications.[12]

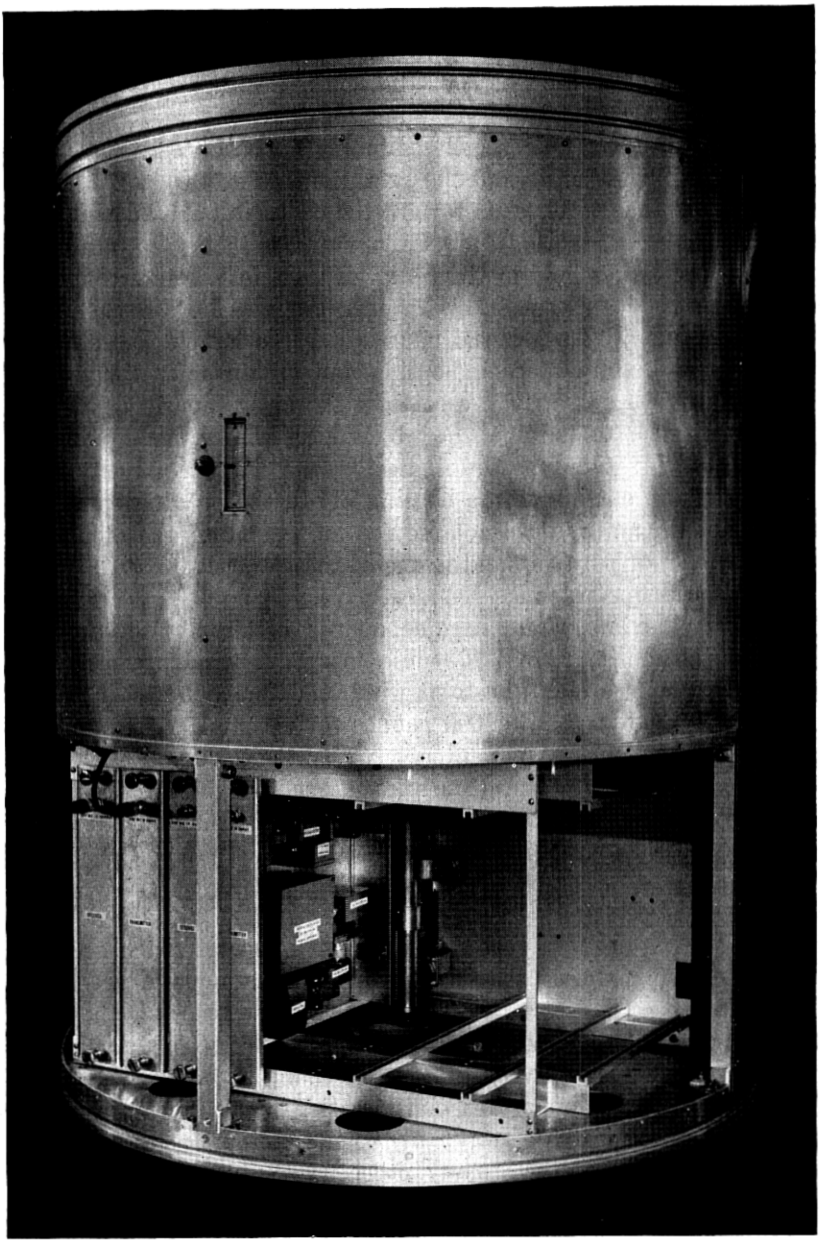


Fig. 13 — Repeater housing and repeater electronics with access covers removed.

The cost of the tower is proportional to its weight. For a given weight, the strength of the tower is a function of the diameter and the wall thickness. The parameter of importance is the end slope which is equal to the antenna beam deflection. These relationships are illustrated in Fig. 14 for tower diameters of 16, 20, and 24 inches. For a 1,650 pound tower, increasing the diameter from 16 to 24 inches decreases the beam deflection from 3 to 1.5 degrees in a 100 miles per hour wind.

The foundation must support the weight of the repeater and tower and the overturning moment caused by the wind load. For all but special situations, a foundation formed of a sufficiently deep steel reinforced concrete cylinder is preferred because it is simple, easily

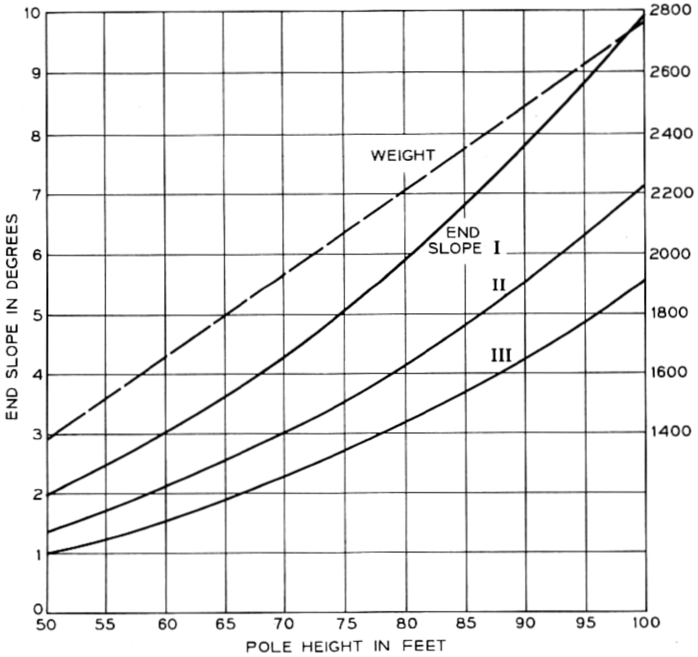


Fig. 14 — Tower end slope and weight as a function of height and diameter assuming a 100 miles per hour wind load of 600 pounds.

Material: Aluminum
Wind pressure: 40 psf

Tower	D_1	D_2	t
I	16″	8″	0.625″
II	20″	10″	0.500″
III	24″	12″	0.417″

installed with a drill rig, and requires a minimum of ground area. A foundation of this type, 15 feet deep and 18 inches in diameter, was used for the Crawford Hill terminal. For soils with low bearing load, a concrete pad is required. A foundation of this type, 9 feet square and 2 feet thick, was used for the Holmdel repeater.

4.3 *Installation and Alignment*

Because of the number of repeaters in a system, it is obvious that field installation and alignment time should be minimal. The procedures used in the experimental system are: (*i*) complete adjustment and testing of the electronics in the shop, (*ii*) antenna alignment and elevation adjustment in the shop, (*iii*) field installation of the packaged antenna and repeater on the tower, (*iv*) erection of tower with complete repeater, (*v*) final vertical and azimuth adjustment of tower, and (*vi*) installation of thermoelectric generator and wiring. In the experimental system, physical alignment of the antenna elements in the shop was sufficient to assure electrical boresight to within 0.15 degree.[10] The towers of the experimental system, with electronics installed, were erected with a crane in about 1.5 hours per tower. Vertical and azimuth alignments were done with a theodolite using alignment marks on the top and bottom tower flanges. From a later measurement it was found that this mechanical alignment was accurate to within 0.3 degree in azimuth and 0.05 degree in elevation.

The heights of the towers in short hop systems are such that cherry-pickers can be used in antenna alignment and for site selection and access to the electronics.

4.4 *Appearance*

Figure 15 shows the Crawford Hill terminal. The antenna weather cover can be seen on the front of the single repeater housing on top of the aluminum pole. The thermoelectric generator is mounted on the side of the pole about 10 feet above the ground and the two propane fuel tank covers can be seen near the foundation. The control building on the left contains the test equipment.

The Holmdel repeater, shown in Fig. 16, has two packages to demonstrate the appearance of a complete repeater. Since it is powered by a thermoelectric generator with no standby source, there is no building or commercial power line associated with the repeater.

V. DISCUSSION

The stability and starting problems of efficient chains of nonlinear amplifiers and varactor multipliers have already been discussed and solutions are given by Dragone.[4] In all harmonic generators, harmonics adjacent to the desired output frequency are present to some degree in the output of the chain. This is the source of the interfering tone apparent in the amplitude response of Fig. 8. Furthermore, harmonics of the 87 MHz oscillator frequency generated by the first X4 multiplier appear as modulation of the fourth harmonic and are

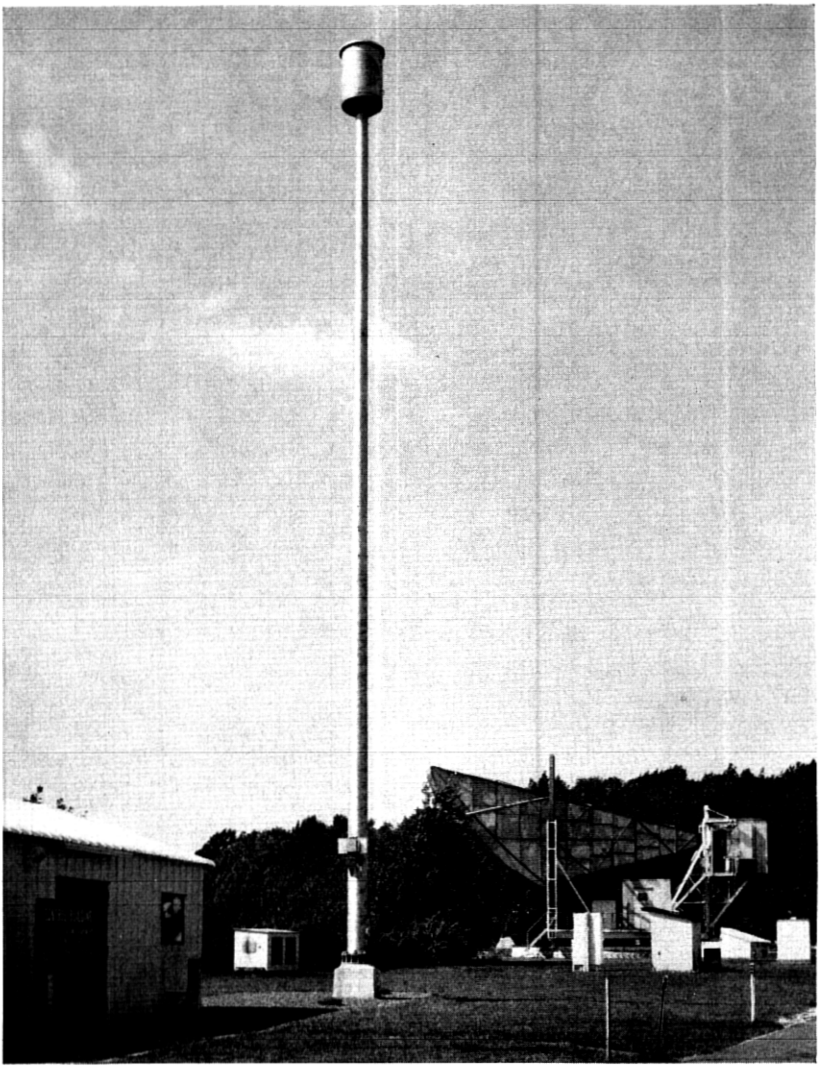


Fig. 15 — The Crawford Hill terminal.

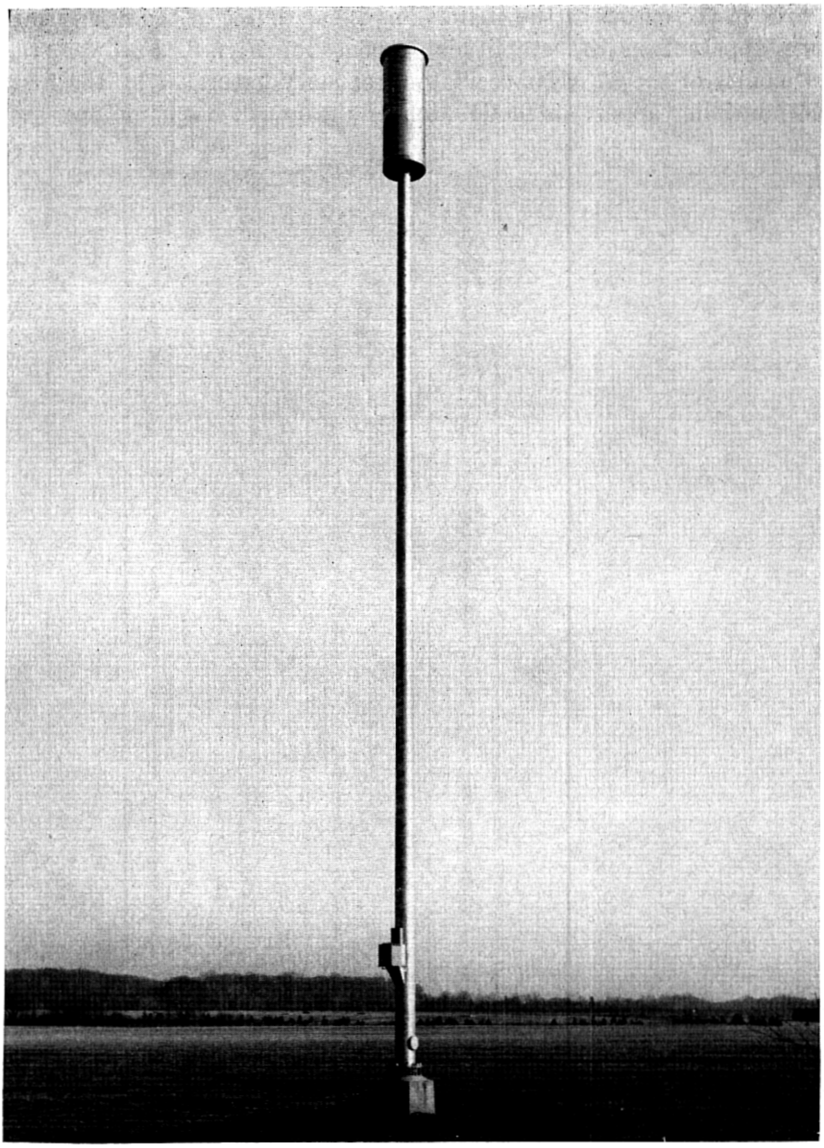


Fig. 16 — The Holmdel repeater.

transmitted through the X32 chain giving rise to additional tones at ±87 MHz around the X32 output harmonics. The best solution for these tone problems is better filtering at the output of the crystal-controlled source and at the pump input to the upconverter and downconverter. This would cost at most a 1 dB decrease in available pump power.

Immediately after field installation it was found that the crystal-controlled power source was sensitive to humidity. The sensitive elements were found to be certain ceramic trimmer capacitors which were particularly susceptible to contamination from handling and soldering. They were replaced by air capacitors which have glazed ceramic for support. As further protection, the low power unit was insulated to obtain several degrees rise in temperature which limits the maximum relative humidity inside the box to about 75 per cent. The system has since operated without degradation through several periods when the relative humidity averaged 99 per cent for several consecutive days.

Failures in thermoelectric generators have caused several interruptions of the system experiment. There are basically two types of failures: burner failures and thermopile failures. Most of the burner failures have been caused by an accumulation of sulfur from the propane in the burner nozzle orifice which changes the fuel-air mixture. Thermopile failures are caused by oxygen contamination and changes in junction material properties. Thermopiles with the required reliability have been made for military and space applications indicating that generators with the required reliability are within the realm of present technology.

VI. SUMMARY AND CONCLUSIONS

A two-hop radio system experiment, operating in the 11 GHz common carrier band, is described in detail. Careful attention has been paid to the fundamental characteristics of systems at frequencies above 10 GHz which must operate during periods of large rain attenuation; these characteristics are illustrated in Fig. 1.

The most important objectives of a system experiment are to demonstrate successful operation in the presence of difficult interface problems and in a real environment. The solution of interface and environmental problems by brute force, such as sprinkling isolators throughout the harmonic generator chain or enclosing sensitive components in constant temperature ovens, is straightforward; unfortunately such an approach could easily be fatal to the system concept in cost and power consumption. The approach taken here has been to determine the performance of components with respect to basic circuit limitations and to approach this performance as closely as possible consistent with the overall system objectives. This long way around, requiring solutions to problems such as stability and starting of high order harmonic generator chains, optimizing varactor up-converters with respect to efficiency, bandwidth and gain, realizing broadband variolossers with low minimum loss, IF amplifiers with low power consumption, and low noise downconverters, is the surest way to good system design.

The system experiment has been in operation since January 2, 1968. Several interruptions caused by faulty operation of the thermoelectric generators occurred and a single interruption was caused by a lightning stroke on Crawford Hill which damaged the output transistors of the main IF amplifier. The inadequate lightning protection for the cables between the tower and the terminal building has been corrected. With these exceptions there has been no degradation in performance of the system.

Most of the objectives of the experiment, discussed in Section II, have been met. Long life and reliability cannot be demonstrated in one year but are certainly indicated by the stable performance of the repeater electronics. As to appearance, who will say?

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