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Microwave Engineering for the Broadcaster

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Broadcast engineers have consistently been the leaders in the use of microwave equipment since the first installations were made over twenty-five years ago. The experience gained by these engineers with actual installations during this period makes it possible now to use sound engineering principles to design systems rather than rely on the trial and error methods necessary in the past. Engineers in the laboratories have advanced equipment design from early lighthouse tubes and reflex klystrons with marginal black and white TV performance to all solid state equipment with negligible distortions of high quality color television signals. The small light-weight low-power drain equipment now available offers the broadcaster new dimensions of flexibility in real time coverage of events outside the studio. The high reliability of modern solid-state equipment removes the tedium of maintenance technician chores and leaves the broadcast engineer free to do more profitable planning and engineering for reducing costs of program production and overall broadcasting operations.

With the rapid advances made during the past seven to eight years in both equipment and system design, it is not necessary for the broadcast engineer to become a communication transmission expert and microwave technician. He can now treat the microwave transmission system almost as if it were a section of hard cable in the system and forget weekly tube meter readings and all night fade watching vigils. In light of this minimum need for concentration on operating details, these discussions are aimed primarily at system planning, equipment selection, and installation.

APPLICATIONS

The flexibility and dependability of solid state equipment makes microwave an indispensable and easily used tool for the modern broadcaster. Its application to almost any kind of transmission problem is now commonplace, and more an exercise in economics than a solution to technical difficulties.

STL (Studio-to-Transmitter Links)

This is the oldest application of microwave in the broadcast industry. Usually only one microwave hop is required in one direction. Both the video and audio program channels may be transmitted over the same microwave link. Many broadcasters find it advantageous to install duplicate, automatically switched, hot standby equipment. In periods of peak activity, the standby equipment from some manufacturers may be removed from the rack and used for portable coverage of outside events. Often broadcasters find that TSL (transmitter-to-studio link) is an economically justified convenience, and if the equipment is capable of rapid tuning to different frequency channels, STL standby equipment may be used for TSL interconnection when not required for protection of the STL. In any event, the second set of equipment is relatively inexpensive because the same antennas, feeders, racks, power plants, etc., are used for both systems. A typical STL transmitter and receiver are shown in Fig. 1.

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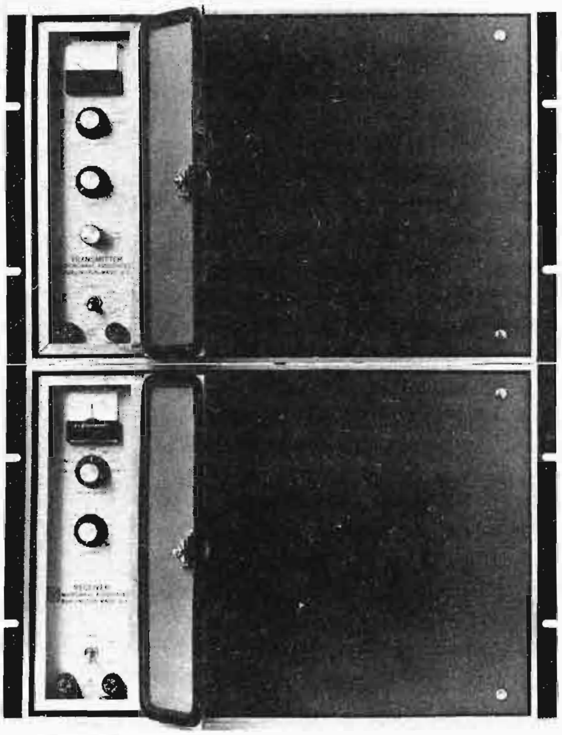


Fig. 1. Typical STL transmitter and receiver. (Courtesy of Microwave Associates, Inc.)

Portable TV Pickup

This application of microwave has shown rapid growth in recent years because of recent technical improvements and portability of all solid state equipment. It is now possible for one man to set up a portable link in a few minutes including switching to the assigned channel frequency. Portable equipment may be used on the ground, on roof tops or on towers as required to achieve line-of-sight transmission back to the studio. When the microwave equipment is installed such that it is not readily accessible, a cable and remote control unit is employed for operating and monitoring the microwave unit at distances up to several hundred feet from the transmitter. Portable equipment should be easily switchable or tunable to several different operating frequencies, and with minimum effort convertible to two or more frequency bands. Frequency agility avoids frequency coordination problems when several broadcasters are simultaneously trying to cover the same event in a local area. As a practical matter, test equipment is not required to set up and operate a portable TV link. Most broadcasters own several sets of portable equipment which can also be used as portable relay repeaters and for standby of the STL or TSL. Fig. 2 shows a typical portable microwave transmitter.

Mobile

This application of microwave is made possible by the low power drain and small size of solid state equipment. Use of mobile microwave adds a new dimension to on-the-spot coverage of any event. Typically, a camera and microwave transmitter are located in a vehicle (van, truck, jeep, blimp, boat, helicopter) which transmits the TV signal back to the program control center. To avoid steering the antenna in the vehicle, omnidirectional antennas can be used. Depending upon the range of operation, a high gain omniantenna may also be used at the control center, or a standard portable receiver with parabolic antenna and manual tracking may be used. Two-way links are often employed, with the link to the vehicle being used for camera sync, cues, zoom control, focus, intercom, etc. Mobile installations are often used for repeater relays especially in aircraft.

An example of mobile application is the Goodyear blimps which are permanently equipped with mobile microwave. The equipment in the vehicle must be rugged and have low power drain. A typical transmitter is shown in Fig. 3, and a 2 GHz omniantenna is shown in Fig. 4.

Backpack

This type of microwave equipment was used extensively for the first time by all TV networks

Fig. 2. Portable microwave equipment. (Courtesy of Microwave Associates, Inc.)

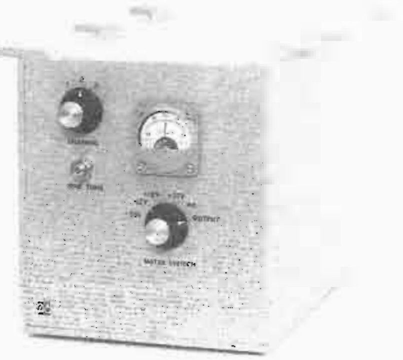


Fig. 3. Mobile microwave equipment. (Courtesy of Microwave Associates, Inc.)

at the 1968 presidential nominating conventions in Miami and Chicago. The link consists of a standard portable video microwave receiver and a narrow band UHF or 950 MHz microwave command transmitter at the program control center, and a special miniaturized video microwave transmitter and narrow band UHF or 950 MHz command receiver in the backpack camera. Special attention to antennas is required to minimize transmission interference resulting from reflections from walls, furniture, etc. Circular polarized antennas are often used to minimize reflection problems.

The narrow band UHF or 950 MHz link is used for cue, focus, zoom, remote antenna tracking, sync, intercom, and on-off power control circuits in the backpack. Typical weight of the backpack microwave transmitter and receiver combined is 10-12 pounds, and battery power drain is 10-12 watts. Ranges up to several miles are achievable if line-of-sight conditions prevail. A typical backpack camera with microwave is shown in Fig. 5.

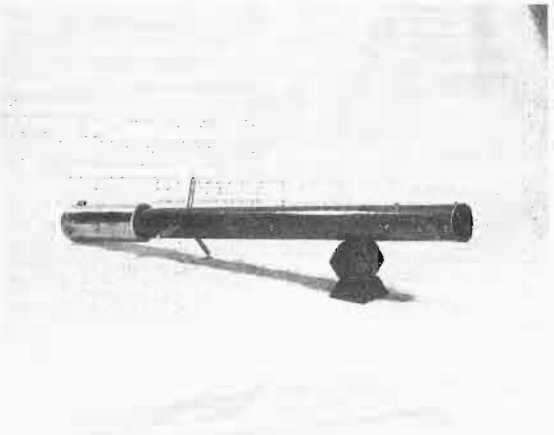


Fig. 4. 2 GHz omnidirectional antenna (6 dB). (Courtesy of Mark Products.)

Fig. 5. Backpack camera with microwave. (Courtesy of ABC Television Network.)

Intercity Relay

This is another old application of microwave in the broadcast industry which has grown rapidly because of increased system reliability and greatly reduced cost and maintenance requirements. Intercity systems are used to interconnect common owned properties, or to provide network service from main line pickup points in one city to another city. Compared with leased common carrier facilities, some broadcasters find superior performance, lower cost, and greater flexibility of operation as reasons for installing their own microwave facility—the decision is no longer dependent upon technical reasons. The systems are usually one-direction, but often two-direction systems are employed to give greater flexibility and the outside plant costs do not increase with the second system. Hot standby equipment is used in most systems to achieve the utmost in reliability. The repeater stations, when required, are usually powered from a float charged battery bank to eliminate system outages resulting from commercial power failures. In long systems automatic alarm reporting equipment is used to remotely indicate power failures, illegal entry, tower lighting failures, battery charger malfunction, high building temperature, etc. Repeater station equipment is usually less complicated than terminal points, and for this reason special low-cost packages have been developed. Fig. 6 shows typical repeater equipment required to relay one TV and program audio channel.

ETV Networks

Most states in the country utilize a microwave network for distribution of educational programs throughout the state. Some of these systems are relatively short, 100 miles or so, while others

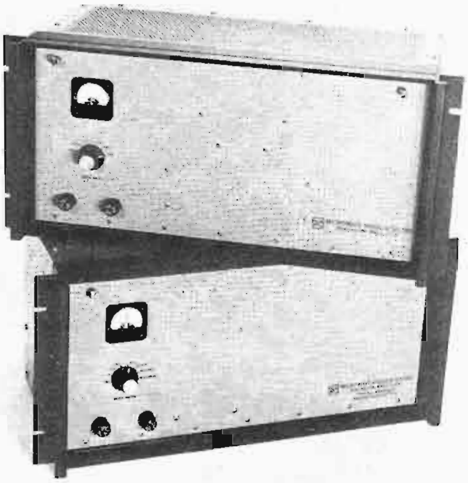


Fig. 6. Solid state remote repeater. (Courtesy of Microwave Associates, Inc.)

extend to many hundreds of miles. Privately state-owned facilities provide excellent service, and the choice over leased common carrier facilities is one of economics and personal preference because of performance or flexibility. Because of the wide variations from state to state in the distance to be covered and the number of repeaters required, two types of equipment have been developed for repeaters—remodulating and heterodyne. The receivers are almost identical in both equipments with the primary difference in the repeater being whether the transmitter accepts an FM modulated IF signal and heterodynes to microwave, or accepts a video baseband signal which directly FM modulates the microwave signal. The choice of one type of equipment over the other is usually based on economics or performance; both methods of operation provide excellent performance, but the heterodyne repeater usually contributes less noise and distortion and costs a little more than the remodulating repeater. The advent of solid state stability in remodulating repeaters removes past problems of high distortion and noise resulting from level variations caused by dying vacuum tubes, so that longer systems can now be built with remodulating repeaters with satisfactory performance.

ITFS (Instructional Television Fixed Service)

In 1963 the FCC allocated the 2.5 to 2.7 GHz band to educators for distribution of instructional television signals throughout one or more school districts. The frequency band is made up of 31, six MHz channels which are utilized for video and sound in much the same manner as the standard broadcasting service. Vestigial sideband transmitters are used for the video with an FM subcarrier at 4.5 MHz in the channel used for audio. In some cases separate visual and aural transmitters may be used. An omnidirectional antenna is often used at the transmitter for wide area multipoint coverage. A parabolic antenna is usually employed at the receiving station to provide high gain and minimum interference. The microwave receiver consists of a translator which converts the microwave signal to one of the standard VHF TV broadcast frequencies. Up to four channels can be converted by one receiver translator if several TV channels are used. The translator output is distributed by coaxial cable throughout the building to standard TV sets. Similar engineering principles apply to designing ITFS systems as to broadcast FM links. Fig. 7 shows a typical transmitter and Fig. 8 shows a translator.

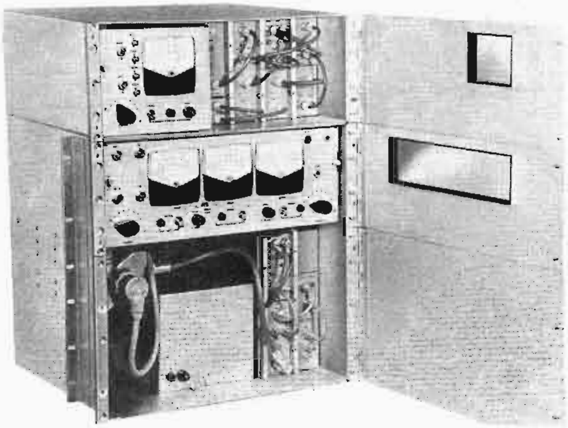
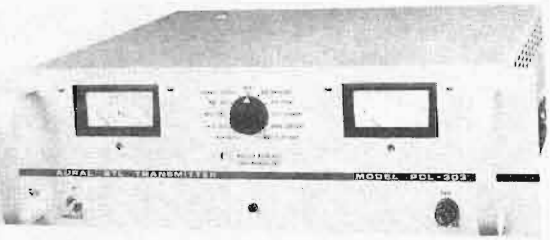


Fig. 7. ITFS microwave transmitter. (Courtesy of Jerrold Corporation.)

Fig. 8. ITFS translator. (Courtesy of Jerrold Corporation.)



9. Audio STL transmitter. (Courtesy of Moseley Associates.)

Audio STL

This is the oldest application of microwave in the broadcast industry and its use is rapidly growing as a result of automated FM and AM transmitter operation and with the availability of all solid state equipment. This service is allocated to the 942 to 947 MHz frequency band which is divided into ten 500 kHz channels. Compared to TV, the microwave equipment is narrow band, but has sufficient transmission capability to handle several 15 kHz program channels as well as numerous telemetry and control tones for automated broadcast transmitter operation. The same system engineering principles apply to audio STLs as to TV, and should be used for establishing performance criteria and designing the transmission link. Fig. 9 shows a typical transmitter and Fig. 10 shows a typical receiver for this service.

Wireless Microphones

This is a new application of microwave, which was used for the first time by the TV networks at the presidential nominating conventions in Miami and Chicago. Previously available wireless microphones operating at VHF or UHF frequencies are subject to severe interference from other services and lack of adequate spectrum for high fidelity studio performance. The new wireless FM microphones operating at microwave frequencies, while more expensive at this time, offer a totally new approach to hi-fidelity sound systems for the broadcasting networks, TV networks, and movie industries. This application is still experimental and the usual engineering rules for fixed point-to-point service are not necessarily applicable. A 1968 change in FCC rules places this service in the 942 to 947 MHz frequency band with a transmitter power limitation of 100 mw, which has proven adequate. As this new microwave service develops, the broadcaster can reduce the audio cost of program production and the complexities of boom microphones in overall TV program production. Fig. 11 shows a typical 950 MHz transmitter.

CARS (Community Antenna Relay Service)

This service was first established almost ten years ago in the 12.70 to 12.95 GHz frequency band on a shared basis with broadcasters. As equipment became available for this application (especially all solid state equipment), use has accelerated and continued to grow at this time. The microwave equipment is normally used to interconnect the head end off-air pickup station with one or more cable distribution systems. The application is characterized by up to ten TV channels being transmitted simultaneously through common feeder and antenna systems. With the advent of all solid state equipment, the trend in this service, as in the broadcast service, has been to treat the microwave system much as a solid piece of cable insofar as the decision to use microwave is concerned. Normally the video and audio are picked off-air together and transmitted together, thereby eliminating the need for separate audio modules in the microwave. Because of the relative simplicity of microwave equipment for this service as compared to broadcast, the equipment cost is usually lower. Both FM and AM equipment is available with the choice being one of economics.

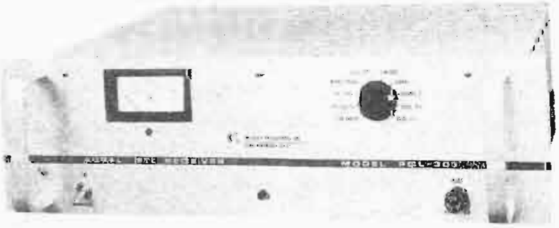


Fig. 10. Audio STL receiver. (Courtesy of Moseley Associates.)

Fig. 11. 950 MHz wireless microphone transmitter. (Courtesy of Microwave Associates, Inc.)

Omni Fixed-Directional Portable

This is a relatively new TV microwave application that is finding rapid acceptance in the broadcast industry because of its simplicity for electronic news coverage. In this application a microwave receiver is installed at the program control center with its high gain (10 dB) omni-antenna elevated enough to provide an unobstructed view of most of the broadcast station's signal area. Often the signal is relayed to the control center through a repeater on a tall building overlooking the city. The microwave transmitter is a standard portable unit which can be set up by one man on location in 5 min or less. Since the microwave receiver antenna is omnidirectional, no effort is required at the program control center or repeater for instant TV coverage of most areas in a given city. The microwave receiver may be installed at the high elevation adjacent to the antenna with a cable extending to a remote control unit located in the equipment room. See Fig. 12.

FREQUENCY SPECTRUM

The FCC has allocated three bands of frequencies for use by the broadcaster for TV relaying and one band for audio relaying. These are referred to as the 950 MHz (narrow band channels for audio program and control circuits), 2 GHz, 7 GHz and 13 GHz bands (wide band channels for TV circuits). Specifically, the frequencies are 942 to 947 MHz (10 narrow band channels), 1990-2110 MHz (7 wide band TV channels), 6875-7125 MHz (10 wide band TV channels), and 12,700-13,250 MHz (22 wide band TV channels). Additionally, the 2500-2690 MHz band is divided into 6 MHz channels for Instructional Television Fixed Service applications. Ten wideband TV channels in the band 12,700-12,950 MHz are allocated to CARS service on a shared basis with broadcasters.

In past years many arguments have ensued on the merits of one frequency band as compared to another. These arguments were often weighted by past experience, or in the case of a manufacturer, by which equipment he had available. Today excellent equipment is available from many manufacturers in all frequency bands, and the old arguments are being modified to reflect the fact that satisfactory systems can be engineered in all frequency bands. It is primarily a problem of understanding the peculiarities of each band and of allowing for these differences when designing the system. In general, the cost of equipment increases with frequency, and other system costs may also increase because of increasing propagation difficulties as operating frequencies increase. For example, an allowance must be made for rainfall at 13 GHz, but can be ignored at 2 GHz. The main point of discussion now is that good service can be obtained in all bands, providing that the peculiar characteristics of each band are considered when the system is designed. With increasing frequency congestion, the choice of band is often based upon availability of frequencies and not upon user preference. The trend to higher frequencies will continue on up to 40 GHz or more in the future.

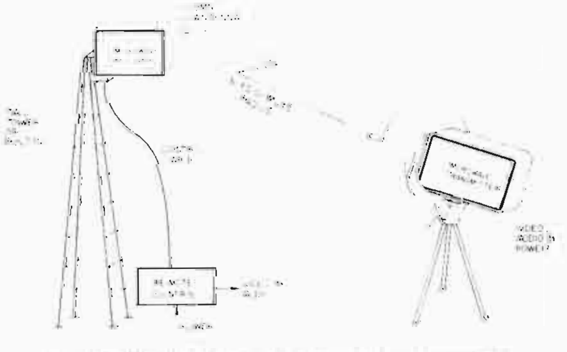


Fig. 12. Omni-fixed directional portable applications.

FCC LICENSING

After designing the microwave system and selecting the equipment an application is made to the FCC for a construction permit. This application is made on FCC Form 313 with the requested equipment characteristics provided by the manufacturer. In many cases the manufacturer previously files equipment characteristics with the FCC and a notation on the FCC Form 313 to that effect is sufficient. After the installation is complete, the broadcaster runs proof-of-performance tests, the results of which are submitted to the FCC to obtain his regular license.

In the case of CARS service, equipment type acceptance procedures prevail at the FCC. The manufacturer must obtain type acceptance of his equipment from the FCC in accordance with parts 2 and 74 of the rules before it will be accepted on the construction request, Form 402.

In order to retain his license, the broadcaster must establish a log at each station. A properly FCC licensed operator assures continual operation in accordance with the FCC rules by duly recording certain specified measurements in the log periodically as required. In addition, the FCC has another microwave requirement which is primarily directed to broadcasters; this is that each microwave transmitter in the system be turned off when not being modulated. This requirement may be met by either manually turning off the transmitter, or automatically turning it off by a modulation detector built into the transmitter.

The broadcaster and others using this *Handbook* should refer to the FCC Rules and Regulations and to their attorneys for complete and up-to-date information.

CONTRACTING

A broadcaster has a wide range of choices available to him for planning and installing a microwave system. He can do his own system engineering and installation then buying all hardware from a single manufacturer with one purchase order; the manufacturer can then be held responsible for meeting contractual performance specifications of each subsystem (antennas, lines, batteries, etc.), as well as the total system. Or, he can do his total engineering including subsystems then buying his hardware from several sources, with each manufacturer responsible only for his own hardware. Or, he can refer the total responsibility by contract to the microwave manufacturer to meet the contractual system performance specification for transmission of signals between two points for a fixed price. Or, he can employ an independent consulting engineer to design the system, prepare equipment specifications, supervise purchasing, and supervise installation either by construction contractors or the microwave equipment manufacturer. Or, he can refer the total responsibility to the manufacturer except for installation which he can do himself under the supervision and checkout of the manufacturer.

There are many other combinations of responsibilities for contracting engineering, furnishing, and installing microwave systems. The choice is based upon many factors best understood by the chief engineer of the broadcaster. Often he is qualified and has the time to engineer and install an STL or purchase portable gear but does not have the time for an extensive intercity or statewide system. In this latter case a consulting engineer, a single manufacturer, or a combination of the two is usually the best choice.

ECONOMICS

Often economic analysis is necessary to compare cost of owning a microwave system versus leasing, and after deciding to buy a microwave system to decide whether to pay cash, finance, or lease the system. Within these comparisons there are several alternates:

1. Contract with one firm for the total broadcast installation with all equipment financed together.
2. Contract for the microwave system separately and finance separately.
3. Finance through one or more manufacturers or directly from a financial institution.

If credit or leasing is used, the broadcaster must be prepared to quickly furnish necessary financial data on his company to establish his credit rating so that the financial part of the contract can be processed quickly without delaying construction and possible revenue income on the investment. If help is needed in making any financial analysis, the manufacturer will usually assist as part of his proposal effort. In order to determine whether a privately owned system versus common carrier service should be used, all costs including installation, terminal, and disconnect charges of the leased system must be made available in order to make comparison with the various ways of financing the cost of the privately owned system. A good textbook on Engineering Economics will provide a wealth of information on the problem.

PERFORMANCE STANDARDS

An individual broadcaster may have a peculiar situation requiring unique specifications, but in most cases well established industry standards with some expansion should suffice. The broadcaster is referred to the following:

Reference Standards

1. EIA STANDARD RS-250-A, *Electrical Performance Standards for Television Relay Facilities.*
2. EIA STANDARD RS-173, *Emergency Standby Power Generators and Accessories for Microwave Systems.*
3. EIA STANDARD RS-195-A, *Electrical and Mechanical Characteristics for Microwave Relay System Antennas and Passive Reflectors.*
4. EIA STANDARD RS-203, *Microwave Transmission Systems* (Definition of Terminology).
5. EIA STANDARD RS-222-A, *Structural Standards for Steel Antenna Supporting Structures.*

In order to provide the broadcaster with a good summary of practical TV microwave transmission and equipment specifications in one place, the following tabulation is given for guidance in specifying equipment for a TV microwave system:

TV Transmission and Equipment Standards

Transmitter power	Manufacturer's spec.
Transmitter frequency stability	±0.05% (max)—portable ±0.005% (max)—fixed

FM deviation (peak to peak)	8 MHz
Modulation	FM
Transmitter output impedance	50 ohms
Transmitter output connector types	
2 GHz	"N" coax
7 GHz	UG-343 B/U
13 GHz	WR 75 (cover)
Transmitter video input impedance	75 ohms
Return loss (min)	26 dB
Transmitter audio input impedance	600 ohms
Portable transmitter tuning range (min)	5% (of op. freq.)
Receiver noise figure (max)	
2 GHz	10 dB
7 GHz	11 dB
13 GHz	12 dB
With low noise preamp (max)	6 dB
Receiver IF frequency	70 MHz
Receiver noise bandwidth	30 MHz
Receiver L.O. stability	.005% (max)
Portable receiver tuning range	Across operating band
Receiver output video impedance	75 ohms
Return loss (min)	26 dB
Receiver output audio impedance	600 ohms
Video input and output level (P-P)	1 volt
Variation	0.7-1.4 volt
Audio input and output levels	+9 dBm
Input adjustment	0 to 20 dBm
Output adjustment	±2 dB
Transmission polarity	Black negative
Video frequency response	
10 kHz to 4.5 MHz	±0.25 dB
Video low frequency response	
Tilt (60 Hz square wave)	1% max
Video differential gain	
50% average picture level	0.3 dB
10% & 90% APL	0.5 dB
Video differential phase	
10, 50, and 90% APL	0.5° max
Video signal-to-noise (EIA weighted)	60 dB (min)
Video signal-to-hum (P-P to P-P)	46 dBm (min)
Baseband spurious tone levels	
1000 Hz to 4.3 MHz	-60 dB (max)
Video transient response	
Max K factor for 2 T pulse	1%
Audio response	
at 50 Hz	+0 to -1.0 dB (max)
100 to 7500 Hz	+0 to -0.5 dB (max)
at 15,000 Hz	+0 to -1.0 dB (max)
(Referenced to 400 Hz)	
Audio signal-to-noise (with window signal)	60 dB (min)
Audio distortion	
50-100 Hz	1.0% (max)
100-1500 Hz	0.5% (max)
7500-15,000 Hz	1.0% (max)
Temperature range (full spec)	0 to 50°C
Operating without damage	-30 to +60°C
Humidity	up to 95% R.H.
Input voltages	
AC (47-63 Hz)	115 v ± 10%, or 220 v ± 10%, or
DC	21-28 v dc, or 42-56 v dc

950 MHz STL Standards

Transmitter power	Manufacturer's spec.
Transmitter frequency stability	±0.001%
Type modulation	FM
Transmitter program input level	+10 dBm
Transmitter multiplex inputs	2 @ 1 volt rms
Transmitter output impedance	50 ohms
Transmitter output connector	"N" coax
Transmitter program impedance	600 ohms
Type receiver	Double heterodyne
Receiver noise figure	9 dB
With low noise preamp	5 dB
Receiver IF frequency	70 MHz & 10.7 MHz
Receiver noise bandwidth	Manufacturer's spec.
Receiver input connector	"N" coax
Receiver input impedance	50 ohms

Receiver program output level	+10 dBm
Receiver multiplex output	2 @ 1 volt P-P
Program channel S/N	65 dB
Program channel frequency response	±0.5 dB (50 Hz-15 kHz)
Program channel distortion	0.75% (50 Hz to 15 kHz)
Mains voltage (47-63 Hz)	115 v ± 10% 220 v ± 10%
Temperature (to spec)	0 to 50°C
(operate without damage)	-30 to +60°C
Humidity	up to 95% R.H.

Dual STL Stereo

Note: Two standard STLs are operated in parallel in one 500 MHz channel to provide L and R program channels. Performance is the same as single channel STL.

Single STL Composite Stereo Operation

L and R frequency response	±0.5 dB (50 Hz to 15 kHz)
L and R distortion	< 0.75% (50 Hz to 15 kHz)
L and R signal-to-noise	65 dB
L and R separation	> 35 dB
Transmitter composite input level	1.5 volt P-P (10 K ohms)
Receiver composite output	6 volt P-P (1 K ohms)

INTERNATIONAL STANDARDS

The preceding standards are quite satisfactory for use in most countries. For additional special information the reader is referred to the following CCIR documents included in Volume IV, Part I from the most recent Plenary Assembly of the International Telecommunications Union:

1. Recommendation 281	Radio frequency channel arrangement
2. Recommendation 282	Special radio frequency channel arrangements
3. Recommendation 382-1	Channel arrangements in 2 and 4 GHz bands
4. Recommendation 383-1 and 384-1	Channel arrangements in 6 GHz band
5. Recommendation 386-1	Channel arrangements in 8 GHz band
6. Recommendation 387	Channel arrangements in 11 GHz band
7. Recommendation 289	Noise in the reference circuit
8. Recommendation 305	Standby equipment
9. Recommendation 401-1	Continuity pilots
10. Recommendation 276	Frequency deviation and polarity
11. Recommendation 402	TV plus single sound channel
12. Recommendation 403-1	IF frequencies
13. Recommendation 405	Preemphasis characteristics
14. Report 289	TV plus four sound channels
15. Report 376	Diversity techniques

Note: 1. EIA Standards may be purchased from:

Electronics Industries Association
2001 Eye Street, N.W.
Washington, D.C. 20006

2. CCIR Documents may be purchased from:

The International Telecommunications Union
Geneva, Switzerland

3. Microwave transmission performance is directly related to receiver input signal level, it is assumed the designer will use a receiver input level compatible with the standards listed in this section.

BASIC REMODULATING TV EQUIPMENT

The basic equipment consists of transmitters, receivers, and power supplies, and these three elements will be covered.

Transmitters

The basic remodulating transmitter consists of a video amplifier (with preemphasis), an oscillator which can be modulated, a power amplifier and frequency multipliers when required to reach the desired output frequency as shown in Fig. 13. Various optional items are available to extend the usefulness of the transmitter; these include: crystal referenced AFC loops to improve frequency stability to 0.005% or better. Off-air demodulator to monitor quality of output at antenna feeder input. Audio subcarrier modulators for transmitting program channels. A switch for rapidly changing frequency to different channels covering 5% or more of the output carrier frequency. Output filters (wideband or channel width) to further reduce spurious outputs and operate with diplexers

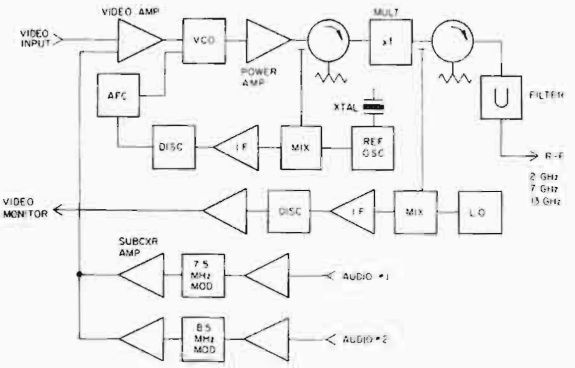


Fig. 13. Remodulating transmitter block diagram.

and duplexers. Special remote control connector plug for portable equipment. Weatherproof housing for portable equipment. Ruggedized packaging for vehicular mobile equipment.

The baseband amplifier is wideband (10 MHz or so) for best linearity and incorporates liberal feedback for stability. A 12 dB preemphasis is used which effectively reduces the possibility of low frequency intermodulation products in the system and improves overall color transmission. Provision is also made for combining one or more audio program subcarrier modulators with the video before frequency modulating the voltage controlled oscillator. The gain of the video amplifier is matched to the modulation sensitivity of the oscillator so that 8 MHz peak-peak deviation is produced on the r-f carrier for a 1-volt peak-to-peak input video signal. The low frequency response of the amplifier extends almost to zero Hz as required for high fidelity transmission.

The transistorized VCO (voltage controlled oscillator) typically runs at 2 GHz where transistors are available with enough power capacity to produce an adequate transmitter output level. As new transistors are developed, the trend will be for higher oscillator frequencies which will result in higher output power and greater power conversion efficiency (lower input power). A number of solid state devices are available which operate directly at the output carrier frequency. The output power of the oscillator may be up to several watts, but is usually lower followed by an amplifier.

The power amplifier consists of one or more broadband stages to provide a gain of 25 to 30 dB at a power output of 8-10 watts at 2 GHz falling off to a watt or less at 13 GHz. As with other transmitter components, the mark of quality is linearity, wide bandwidth (10% or more of the operating frequency) and long-term stability. The amplifier should operate on any assigned frequency channel in the band without retuning.

Early solid state equipment all used frequency multiplier, and the number of varactor diodes used in the frequency multiplier chain depended upon the output operating frequency—typically one multiplier was required for 2 GHz, two for 7 GHz, and three for 13 GHz. These multipliers consisted of varactors, impedance matching circuits, cavities, and filters to efficiently operate over a wide band of frequencies with minimum spurious output signals. No tuning was required to cover up to 10 assigned frequency channels in the three operating bands. Typical power outputs from the varactors was 2 watts at 2 GHz, 0.5 watt at 7 GHz, and 0.25 watt at 13 GHz. At the present time operating frequencies of solid state components is increasing so that the need for frequency multipliers will not exist for any frequency band in the near future.

The AFC option utilizes a crystal controlled source which feeds one side of a mixer. The other side of the mixer is fed with a sample of the transmitter frequency. The mixer output is an IF signal which is amplified and demodulated by a temperature compensated discriminator. The dc output from the discriminator is the carrier frequency error voltage which, when applied through a dc amplifier to the VCO, keeps it on its assigned frequency.

The off-air monitor is essentially a microwave receiver which demodulates a sample of the transmitter output signal for monitoring. To be of maximum value as a transmitter test tool, the monitor signal should be of high quality even though it is slightly more expensive than slope detectors and other lower cost devices sometimes used.

The subcarrier modulators are actually FM transmitters operating in the 7 to 8 MHz frequency range and typically deviated 140 kHz rms. The output of the modulator is mixed with the video signal at a level of -12 to -20 dB below the peak level of the video signal. The modulator may or may not use preemphasis depending on the equipment designer's choice and needs.

The frequency switcher shifts the operating bias on the oscillator to change its frequency and when AFC is used switches crystals in the reference oscillator. Since all circuits are wideband, no tuning is necessary when frequency is changed.

The transmitter output filter is used when the transmitter is diplexed with another transmitter or duplexed with a receiver, or to reduce spurious levels. The filter may be broadband covering 5% or more of the spectrum, or narrow band covering a single assigned channel.

For portable applications, a special weatherproof housing is required which is easily fitted, with an antenna, to a tripod. If remote control is used, special wiring and a connector are installed for mating with the remote control cable. When the portable transmitter is used in hot weather in direct sunlight, a sunshade is recommended to prevent excessive heating.

Equipment for mobile applications must be packaged in a rugged manner to withstand the high degree of shock and vibration experienced in most vehicles. Also size and weight become more important so that special precautions must be used to keep the high density packaged components from overheating.

To prevent interference to or from broadcast microwave equipment, special precautions must be taken for RFI filtering and shielding. The total unit is usually enclosed in an RFI proof case with special gaskets at all access doors and panels. Additionally, all input and output electrical connections must be RFI filtered. Without these precautions, considerable difficulty can be expected, since broadcast microwaves equipment often operates in close proximity to high powered transmitters.

Receivers

All TV microwave receivers are typically super heterodyne with a 70 MHz IF amplifier as shown in Fig. 14. For broadcast work the local oscillator and mixer must be broadband for best stability and to eliminate the need for tuning when switching to a variety of different frequencies.

The mixer typically operates over an octave of frequency and may be single ended or balanced depending upon the need to suppress certain types of noise from the local oscillator. Typically construction is coaxial at 2 GHz and waveguide at 7 GHz and 13 GHz. The mixer determines the noise figure of the receiver which is in turn largely dependent on the diodes used. Noise figures of 8 to 11 dB are typical over the 2 to 13 GHz bands. The mixer function is to produce an IF frequency by subtracting the local oscillator frequency from the receiver carrier frequency.

The local oscillator carrier is usually crystal controlled to 0.005% or better of the output frequency. Fundamental oscillators are usually used, but lower frequency oscillators followed by multipliers are also sometimes used. For frequency switchable equipment up to 10 crystals may be used or a suitable synthesizer.

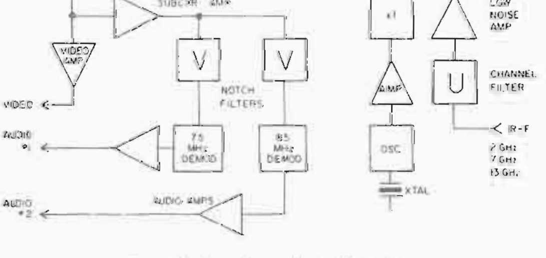


Fig. 14. Receiver block diagram.

The 70 MHz IF preamplifier is often mechanically integrated with the mixer to achieve best overall noise figure of the reciver. The preamplifier typically has 25 dB gain and is 50 to 60 MHz wide.

Optimum receiver noise performance is achieved when the minimum necessary bandwidth is used—this is typically 30 MHz to the 3 dB points for TV transmission. Since the basic IF amplifier circuits are 50 to 60 MHz or more wide, a lumped constant filter located between the pre-IF and the main IF is employed to reduce the noise bandwidth of the receiver to 30 MHz. The characteristics of this filter must be carefully controlled for good phase and amplitude linearity.

The main IF follows the filter and provides typically 65 dB of gain. In both pre and main IFs, common base transistor design is used which effectively isolates the transistor characteristics from the overall amplifier performance characteristics which are determined primarily by the interstage coupling circuits. With this design approach, the receiver characteristics are essentially independent of the transistor characteristics which may vary widely with temperature. The output level of the IF is 0.5 v or +7 dBm. The input microwave level to a typical receiver may vary from -25 to -80 dBm during fading conditions. Since +7 dBm output is required, the gain needed varies from 32 dB to 87 dB. In order to keep the output constant, 60 dB of AGC is typically used to regulate the 90 dB gain in the two IF amplifiers between 40 and 90 dB. Since portable and mobile equipment operates over wide ranges of distance, it is important that receivers have at least 60 dB of AGC.

The limiters are an important part of an FM receiver because they effectively eliminate the effects of AM variations on the signal. These AM variations will contribute noise at the output of the discriminator and have an appreciable effect on threshold performance. Typically 20 dB of limiting is used.

The discriminator demodulates the FM signal back to video. In a wideband TV system, it is important to keep the discriminator linear over a wide bandwidth, typically ±5 MHz or more about the center 70 MHz IF frequency. Nonlinearity will produce distortion and noise on the signal by increasing intermodulation between various components of the TV signal.

The video amplifier brings the discriminator output signal back up to one volt. It also includes a deemphasis network which is exactly matched to the transmitter preemphasis network so that an overall flat frequency response is achieved through the system. The video amplifier includes a low pass filter to reduce the level of the audio subcarriers at the video output. While the degree of audio subcarrier rejection is not extremely important in TV microwave signals, it is typically 30 to 40 dB below peak video levels. A high degree of feedback is used in the video amplifier to achieve maximum stability.

The audio subcarriers are extracted from the video by notch filters tuned to each subcarrier frequency. The subcarrier demodulator is a high fidelity 7 to 8 MHz FM receiver which delivers +9 dBm audio with low distortion and 15 kHz fidelity.

The preselect filter at the receiver input is used to improve selectivity, prevent local oscillator radiation, and suppress image frequencies. It typically consists of five or more filter sections designed and tuned to cover several channels in switch tunable systems or a single channel in fixed signals. The passband characteristics must be closely controlled to avoid phase nonlinearities in the system.

The same comments made for the transmitter regarding portable and vehicular applications apply to the receiver.

Power Supplies

Most microwave equipment uses several different voltages to power the various active circuit components. These are usually low voltages of 12 to 35 volts that must be highly regulated and filtered for best performance. The power supply function is to convert the ac or dc main supply voltage to those required in the equipment.

Fig. 15 is a block diagram of a typical power supply system. Ac units consist of a transformer and rectifiers to obtain the unregulated operating voltages. Various types of transistor regulators are used to keep the operating voltages within a narrow range of variation. In dc units the battery voltage is first converted to ac by a chopper or inverter after which operation is similar to the ac. Good designs usually employ protection circuits on both input and outputs to protect the power supply from surges, load short circuits, and lightning.

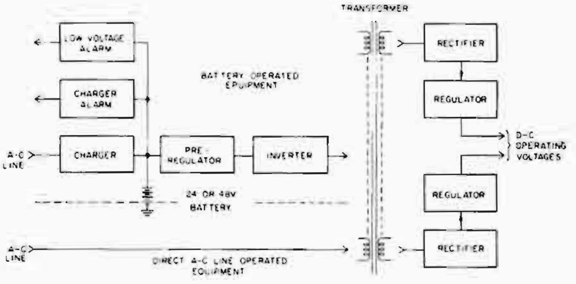


Fig. 15. Power supply block diagram.

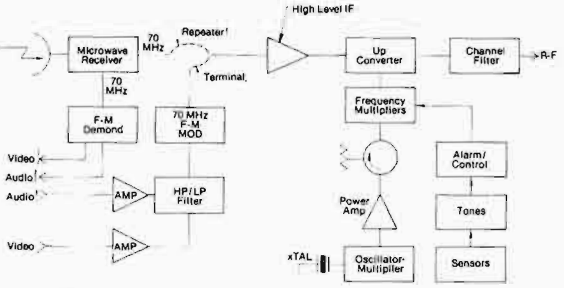


Fig. 16. Heterodyne transmitter block diagram.

BASIC HETERODYNE TV MICROWAVE

The receiver in a heterodyne system is almost identical to the remodulating receiver already discussed. The only difference being that two 70 MHz outputs are obtained from the IF, and the limiter, discriminator, and video amplifier are usually referred to as the demodulator. One of the 70 MHz outputs feeds the demodulator when used at a repeater and the other feeds the heterodyne transmitter.

The heterodyne transmitter block diagram is shown in Fig. 16. It consists of a high level IF amplifier and a high level microwave source both of which feed a high level up convertor mixer. The high level source is similar to that used in the remodulating transmitter except it need not be modulated. The mixer heterodynes the 70 MHz IF input signal up to a microwave signal ±70 MHz different from the source frequency depending upon the sideband selected. The solid state heterodyne transmitter typically has a lower power output than the remodulating transmitter because the heterodyne loss is about 4 dB. Thus a 2 watt source produces an 800-milliwatt heterodyne transmitter. For this reason traveling wave tubes or solid state amplifiers are used after the heterodyne mixer.

At a repeater the 70 MHz IF input to the transmitter comes from the second receiver IF output at a level of 0.5 volt. If the heterodyne transmitter is used at a terminal station, the video signal first modulates a 70 MHz FM transmitter (modulator) which then feeds the transmitter.

Because the signal is relayed through a repeater station without going through the modulator or demodulator, the noise and distortion of the modulator and demodulator is eliminated and the relay is made with less noise and distortion than through a remodulating repeater.

In long-haul microwave systems, heterodyne repeaters are a necessity to keep end-to-end noise down to reasonable levels. In short-haul systems the remodulating system offers comparable performance at a lower cost and with greater flexibility. For systems up to 8 to 10 hops the remodulating system is normally used, while for longer systems heterodyne equipment is normally used. The other elements in a heterodyne system are not appreciably different from those in a remodulating system.

RF MULTIPLEXERS

When two transmitters or two receivers on different frequencies are connected to a common feeder line and antenna, the combining process is called diplexing. When a transmitter and a receiver are connected to a common antenna, the combining process is called duplexing. When more than two units are connected to a common antenna, the combining process is called RF multiplexing (see Fig. 17).

RF multiplexers usually consist of combinations of bandpass filters and ferrite circulators so that each transmitter or receiver sees only the antenna as a load rather than seeing each other. Unless each unit is isolated from the other, intercoupling takes place resulting in interference between the microwave signals. For example the transmitter and receiver in a duplexed system must be isolated by over 100 dB. Of this amount the ferrite circulator contributes about 20 dB and the filter 80 dB or more.

When channel separations are too close to achieve necessary isolation with circulators and filters, dual cross polarized antennas are used with two feeds to provide another 30 dB or so of isolation between channels assigned to each of the two feeds. The two feeds may be in the same parabolic reflector or in different reflectors where near field isolation of up to 100 dB may be achieved depending on type of reflector and relative location of the two reflectors. Thus the RF multiplexer may include the antenna system in some cases.

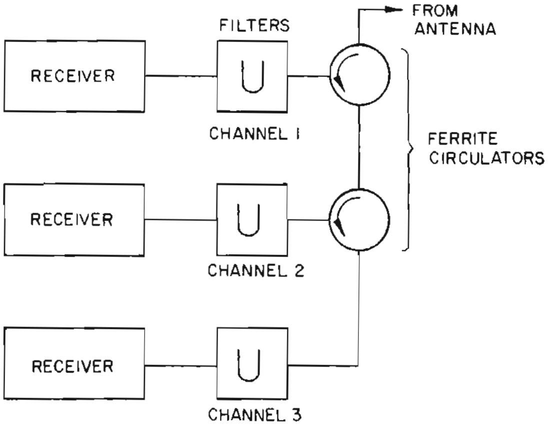


Fig. 17. RF multiplexing block diagram.

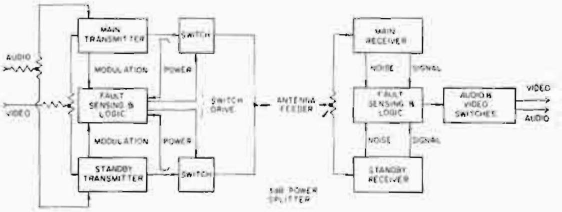


Fig. 18. Hot standby block diagram.

The most complicated and difficult RF multiplexers are required in CARS systems where as many as ten 25 MHz TV channels are sometimes transmitted in parallel in a 250 MHz segment of spectrum. Cross-polarized special-shrouded parabolic reflector antennas are required to achieve the necessary isolation between receivers.

HOT STANDBY

Maximum equipment reliability is achieved by installing duplicate equipment with one equipment automatically replacing the other in the event of failure. The failure mode is detected by comparing several monitored performance indicators in the two equipments and switching when this comparison shows a preset difference. A typical arrangement is shown in Fig. 18.

The same input signal is fed to both transmitters. One transmitter at a time is connected to the antenna through an RF switch which is activated by the logic comparison circuits. Two performance indicators (modulation and power) are normally monitored. Modulation is monitored by detecting the presence of a continuity pilot fed through the system along with the picture and sound signals. This pilot may be a tone operating above the picture and sound spectrum, or for TV microwave the video sync pulse at 15.75 kHz makes an effective pilot.

The RF signal into the receivers is split into two paths—one for each receiver—with a 3 dB loss. The pilot is monitored at both receiver outputs along with receive signal levels. If either of these indicators in one receiver drops below a preset value as compared to the other receiver, the output is switched to the receiver indicating best operation.

The logic circuits must provide an indication when switching has occurred, and prevent switching during periods of fading, loss of input signals to the system, or when the standby unit is inoperative. It should also include visual indicators showing which units are operating at a given time as well as equipment failure. Manual override switches are incorporated to permit disconnection of either equipment for maintenance.

DIVERSITY

Two types of diversity are used in TV microwave systems: frequency and space. In frequency diversity systems identical video and sound signals are transmitted through two different microwave equipments operating on frequencies spaced 4 to 5 percent apart and coupled to a common antenna system. In space diversity two receiver antennas are used with vertical spacing determined to avoid simultaneous fading at both antennas. In each type of system the output is selected from the receiver with the least noise. In general, FCC practices preclude the use of frequency diversity by broadcasters to conserve frequency spectrum. Many other countries use frequency diversity with no restrictions. In both types of operation the receiver logic circuits are identical. Fig. 19 shows a typical configuration for space diversity.

Diversity combiners are of two types: switched and combined. The switch type is similar to the hot standby switcher except transfer between receivers occurs at a preset difference in noise from the two receivers rather than on complete failure as used for standby arrangements. Combiners are universally used for medium density telephone microwave systems, but are still somewhat experimental for wideband TV microwave systems. When used, the functional objective is to combine the two receiver outputs in a way that always produces the optimum signal to noise. Since receiver noise adds on a power (random) basis, and video adds on a voltage (phase) basis, the combiner will give a 3 dB improvement in signal to noise when both receiver input signals are equal in level. The monitored noise for the combiner may be either out-of-band noise, or IF AGC voltage.

LOW NOISE AMPLIFIERS

System fade margins and performance may be improved by using a low noise amplifier at the receiver input. The gain of these amplifiers is typically 15 to 20 dB with a noise figure of 4.5 to 6.0 dB, depending on frequency. Tunnel diodes are used at 7 and 13 GHz and high frequency transistors are used at 1 and 2 GHz. These noise figures represent a 4 to 5 dB improvement in performance for most equipment. The units are available for use inside the receiver or are provided in weatherproof housings for installation outside near the antenna. In the latter case the loss of the transmission line is eliminated and the system improvement is further increased. Another application of the low noise amplifier is between two back-to-back dishes operating as a passive repeater. The low noise amplifier is a useful tool to the microwave design engineer, and its use in the system should not be overlooked.

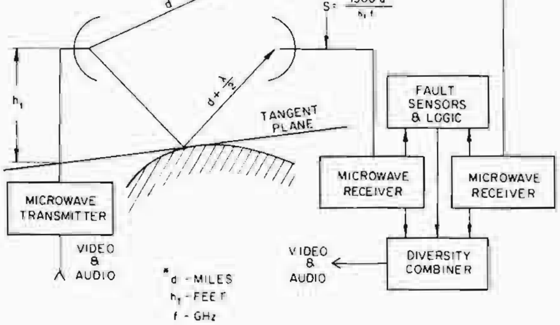


Fig. 19. Space diversity block diagram.

REMOTE CONTROL

In portable and STL applications it is often desirable to locate the microwave equipment at a distance from operating personnel. It may also be desirable to remotely control and monitor the microwave equipment. For this purpose a flexible multiconductor cable is used between the microwave equipment and a remote console. The remote control option includes equalizers for the cable, amplifiers to overcome cable loss, remote main power control, and all equipment metering points. When properly designed, the remote control option will not impair overall transmission quality. Fig. 2 shows a typical remote control console. The distance between equipment and remote control point may be up to several hundred feet. The cable should be weatherproof and remain flexible down to very low temperatures.

ALARM EQUIPMENT

Operating status of remote repeaters is often monitored at one end of the overall system. To accomplish this function, a special alarm channel is multiplexed on the baseband along with the video and sound signals. The monitored alarm indicators are then scanned with a digital scanner which generates pulsed codes indicating the status of each alarm. These pulses key a tone generator which is fed into the alarm channel. At the receiving display station, the pulsed tone is demodulated, usually with a binary counter circuit, and the demodulated code is displayed on a lamp panel which indicates the status of each alarm at each repeater.

Typical alarms are:

1. Transmitter failure;
2. Receiver failure;

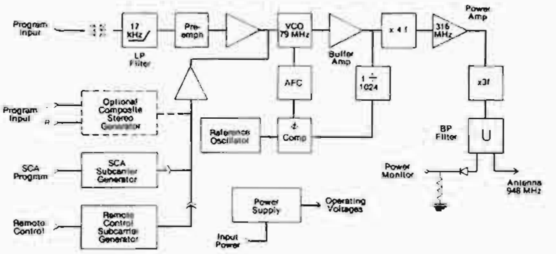


Fig. 20. 950 MHz audio STL transmitter block diagram.

3. Power failure;
4. Battery charger failure;
5. Tower light failure;
6. High building temperature;
7. Illegal entry; and
8. Engine generator fuel.

950 MHz STL EQUIPMENT

Functional block diagrams of 950 MHz audio STL equipment are quite similar to TV microwave equipment. The major difference is that the 950 MHz equipment is narrow band as compared to TV. For this reason the equipment design techniques are somewhat different. The baseband width of an audio STL is typically 100 kHz, while TV microwave baseband width is 10-12 MHz. Figs. 20 and 21 show block diagrams for a typical 950 MHz STL transmitter and receiver. Because solid state components are now available, the need for multipliers has almost disappeared.

The 950 MHz STL equipment is used for audio program transmission and remote control. Stereo FM is transmitted either through a dual STL operating in one 500 MHz channel, or through a single STL using a composite stereo baseband signal. The dual STL stereo system has the added reliability of equipment redundancy, and the composite stereo STL has the advantage of economy.

Transmitter

The transmitter input consists of a multiplexed baseband signal including program channel, telemetering, and control tones and SCA. The baseband amplifiers raise the input levels to the correct level to FM the VCO modulator oscillator. One hundred percent modulation is typically ±40 kHz.

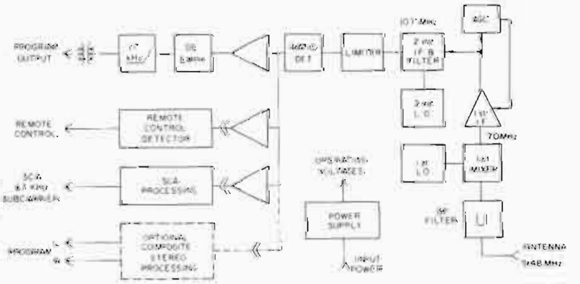


Fig. 21. 950 MHz audio STL receiver block diagram.

The modulator oscillator may be FM or phase modulated. Phase modulation has the advantage of being directly crystal controlled, whereas FM requires an AFC loop; but direct FM gives superior performance especially at low baseband frequencies. The decision as to which type of modulation to use is normally a compromise between cost and required performance. The oscillator runs from 80 MHz to 947 MHz for FM transmitters and 11 MHz for phase modulated transmitters. The higher multiplication factor for phase modulation is required to achieve rated FM deviation.

The oscillator is buffered from the first multiplier if used by an amplifier. The first multiplier output is typically 316 MHz. The 316 MHz signal is further amplified and then tripled to 948 MHz. Since the 950 MHz equipment need not operate on multiple frequencies on a switched basis, all circuits may be narrow banded for maximum gain and efficiency. Typical solid state power output is 4 to 10 watts.

Receivers

The receiver is typically double heterodyne to reduce cost, improve selectivity, and simplify design. The first IF is usually at 70 MHz and the second IF with most of the receiver gain and selectivity is at a lower frequency—often 10.7 MHz where standard FM broadcast receiver parts are available. The local oscillator is crystal controlled. The limiter/discriminator is similar to TV microwave except it operates at a lower frequency over much less bandwidth. The video amplifiers deliver the specified signal level to the various program channel, telemetering, control, and SCA outputs. Since bandwidth of the 950 MHz receiver is one-hundredth or less of the TV microwave receiver, its sensitivity is 20 dB or better than the TV receiver. This increased sensitivity decreases antenna requirements so that simple corner reflectors are often used.

Ancillary Equipment

The 950 MHz STL system may include numerous devices associated with the broadcast transmitter operation. Digital alarm scanners, automatic data loggers and printers, and remote control devices are available. Remote telemetering is usually incorporated using VHF equipment at 100 MHz for the return path between FM transmitter and studio.

Duplex Operation

If a TSL link is required, transmitters and receivers may be combined to a common antenna in the same manner as for TV microwave. Because of the limited spectrum available, transmitter to receiver spacing is quite close in frequency and requires special duplexing precautions.

ANTENNA SYSTEMS

Several different types of antennas are used in a TV microwave system. Omnidirectional vertical stacked arrays are used for portable and vehicular applications. Parabolic reflector antennas are used for STL, intercity, ETV, and CARS systems. Corner reflectors and modified parabolas are sometimes used for 950 MHz STLs. Horn or shrouded parabolic antennas may be used for high front-to-back isolation ratios. Simple dipoles are often used for back pack and wireless microphone equipment. Selection of the antenna is usually based upon the application and the antennas available. The reader is referred to EIA Standard RS 195A for mechanical and electrical specifications.

Isotropic

The isotropic antenna is a hypothetical antenna used as a reference against which the gain of other microwave antennas are measured. The term dBi denotes gain over an isotropic antenna. The isotropic antenna by definition has a radiation pattern which is a perfect sphere. The power density per unit area at a point in space due to the power P_T radiated by an isotropic antenna is

$$P = \frac{P_T}{4\pi d^2} \qquad [1]$$

where: d = Distance from radiator.
$4\pi d^2$ = Surface area of a sphere with radius d.

By definition, the effective area of an isotropic antenna is $\frac{\lambda^2}{4\pi}$ and the power received P_i is Equation 1 times the isotropic area, or

$$P_i = \frac{P_T \lambda^2}{(4\pi)^2 d^2} \qquad [2]$$

Other Antennas

For other antennas of effective area A, the power received P_R is from Equation 1,

$$P_R = \frac{P_T A_{ef}}{4\pi d^2} \qquad [3]$$

The gain of an antenna is defined as the ratio of its radiated or received power to that of an isotropic antenna. The ratio of Equation 3 to Equation 2 gives the gain (G) as,

$$G = \frac{4\pi A_{ef}}{\lambda^2} \qquad [4]$$

where: A and λ are in same units of measurement.

$$G = 12.77\, A_{eff}f^2 \qquad [5]$$

where: G = Gain
A_{ef} = Effective area in square feet
f = Frequency in GHz.

Using Equation 5, the gains of various types of antennas are listed below:

Type	*Gain (dBi)*	
Parabola	$10 \log 5.5\, D^2f^2$	[6]
Horn (optimum)	$10 \log.\ 10.3\, Af^2$	[7]
Omnidirectional (stacked array)	$10 \log 2\, Lf^2$	[8]

where: D = Diameter of parabola-feet
A = Mouth area of horn-feet^2
L = Length in feet
f = Frequency in GHz.

Parabolas

The parabolic antenna is available with several useful refinements. Radomes, heated and unheated, are available to prevent icing which rapidly reduces efficiency, especially at the higher frequency. Special shrouds are available to improve the radiation pattern and increase front-to-back gain ratios. Dual cross-polarized feeds are available which provide 25 dB or so of isolation between two signals using the same reflector. Antennas at 1 and 2 GHz normally use coaxial dipole feeds while those at 7 and 13 GHz usually use waveguide horn feeds. Standard mounting structures are available for attaching the antenna to a 4-in. OD pipe, along with clamps which can be loosened for aiming the antenna after installation on a tower. Special light weight 950 MHz antennas sometimes mount to a 2-in. pipe. Special roof mounts are available for aiming the antenna upward when passive reflectors are used on the tower. Feeders are air tight so that when pressurized moisture will not enter and reduce feed efficiency. At the lower frequencies grid and mesh construction is often used to reduce weight and wind loading on the towers.

Horns

Several variations of the horn antenna are available for microwave use. They are usually characterized by better radiation patterns than the parabola. For reasons of economy and form factor, they are not often used by broadcasters.

Omni

The omnidirectional antenna is characterized by a radiation pattern resembling a doughnut. Gain is achieved by reducing radiation in the vertical direction. They are often used to eliminate the need for tracking in mobile systems with typical gains of 6 dB on the vehicle or 10 dB at fixed points. The higher gain antenna is not used on vehicles because of signal loss when the vehicle banks during turning. A 2 GHz omniantenna is about 16 in. long for 6 dB gain. The antenna is typically mounted on top of surface vehicles, or hinged beneath aircraft so that it may be dropped to a vertical position after takeoff. See Fig. 4 for a 6-dB omni at 2 GHz.

Passive Reflectors

Passive reflectors are often used at 7 and 13 GHz instead of feeder waveguide to effect radiation at the top of the tower. The choice to use passive reflectors usually reflects lower cost or transmission loss or both. The installation consists of a parabola near the equipment aimed at a reflector tilted about 45° with the earth which reflects the energy away from the tower in a horizontal line. The efficiency of the reflector depends upon how well it is illuminated by the parabola, which in turn is a function of spacing and size ratio between the reflector and parabola. Curved reflectors are sometimes used to improve efficiency by 2 dB or so.

Analysis of the gain of a parabola/reflector antenna system is complex, but useful relationships have been determined empirically which are shown on the transmission work sheet in Fig. 22. These curves may be used to determine gain of any size combination for use in system calculations.

Adjustment of reflectors in the field requires skill but is accomplished with the assistance of surveying equipment for initial adjustment and trial and error for best received signal after the equipment is installed. Most popular sizes are 6 X 8, 8 X 10, 8 X 12, and 10 X 15 feet fed by 4, 6, 8, and 10 foot parabolas.

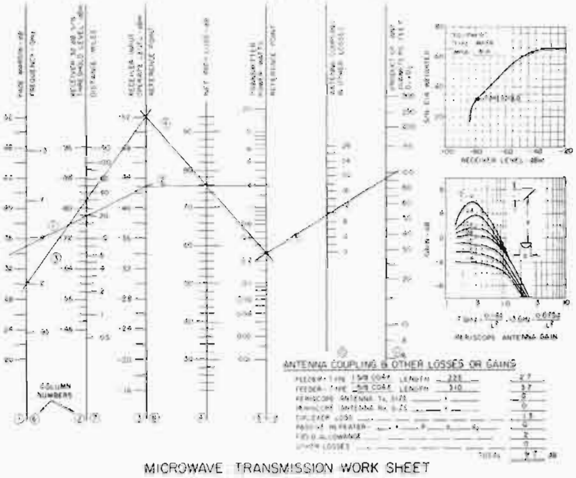


Fig. 22. Transmission calculation worksheet.

TOWERS

Microwave towers are of two types: guyed and self-supporting. The guyed tower is most economical, but requires more land area. The self-supporting tower is used where land is expensive or almost unavailable. EIA Standard RS-222A is the most useful document available for purchasing specifications. All manufacturers meet this minimum requirement. Both types of towers should be equipped with suitable means for safe climbing in case of maintenance.

Installation and height restrictions are imposed by both the FAA and local ordinance. These factors should be checked when making tower decisions. Also towers above certain heights require lighting as specified by FAA rules. Generally, lights must be observed daily by personal observation or by automatic alarm system. Tower painting is specified by the FAA and repainting is required at specified intervals. See Fig. 23 for a typical tower and antenna installation. Microwave equipment manufacturers can provide advice on the most suitable tower for a particular application.

BUILDINGS

Wood, masonry, and metal buildings are used at remote repeater stations. The choice depends upon economics and local ordinances. Concrete buildings are best for security against vandals and require less maintenance. Buildings should be well ventilated or air conditioned to limit temperature extremes—heat is often required in colder climates. The typical repeater building is 8 × 10 feet, which is adequate for electronic gear and standby power. Other factors are important such as drainage, grading, grounding, access, etc.; reference to EIA TR-142 will prove helpful in specifying the building.

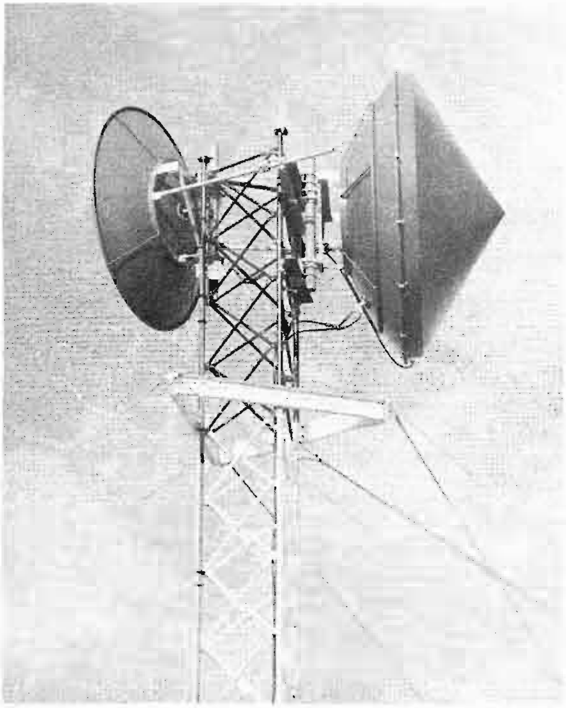


Fig. 23. Typical tower and antenna installation.

POWER PLANTS

With improvements in equipment and systems engineering, the reliability of the main power source becomes more important. With solid state equipment which requires low power and voltages, batteries are the most popular form of standby power. If prolonged commercial power failures are anticipated, engine-generator sets are used to recharge the batteries. In some remote areas, gas fueled thermoelectric generators are used. The reader is referred to EIA Standard RS-173 for further information on standby generators.

Industrial lead-calcium or lead-antimony acid batteries are most often used. Both types are reliable and the choice is often one of personal preference. The one advantage of lead calcium is that equalizing charges are not required which reduces maintenance. The float charge voltage is 2.15 volts per cell for lead-antimony and 2.2 volts per cell for lead-calcium. Batteries should be installed in well-ventilated areas to reduce the possibility of explosion from escaping hydrogen gas. Battery banks usually consist of 12 or 24 cells (24 or 48 volts). Cell voltage typically varies over a range of 1.75 to 2.35 volts when completely discharged and when at maximum charging rate. The communication equipment must be capable of accepting this variation. Battery size is usually selected for a minimum 8-hour capacity and a typical 24-hour capacity. Present day batteries are quite reliable and require little attention for many years. Batteries are also effective filters to protect solid state equipment from power line surges.

Battery chargers operate from standard commercial power and actually provide the power to the equipment with the battery floating as a standby device. Good chargers should incorporate protective devices to limit charging current and to protect against line surges. Alarms for charger and line voltage failure should also be available. Purchase of batteries and chargers from the same source of supply is recommended to insure compatibility.

Batteries and chargers are sound investments which will add many hours of operating time to the average microwave system.

ANTENNA FEEDERS

Microwave equipment is connected to the antenna with either coaxial cable or waveguide. Coax is used for 1 and 2 GHz and may be either foam filled or air dielectric. Waveguide is used for 7 and 13 GHz and may be either rigid rectangular waveguide, elliptical flexible waveguide, or circular waveguide. Short sections of flexible rectangular waveguide are often used to simplify installation. In addition to the lines, various hangers, clamps, bending tools, hoisting grips, and pressurizing equipment are required for installation. It is recommended that transmission lines be installed in continuous lengths to avoid potential problems with splices or joints.

The Andrew Corporation, Orland Park, Illinois, provides a wealth of information in its standard catalogue on the characteristics of feeder systems. Typical losses vary from 1.0 to 10.0 dB per hundred feet, depending upon the type of feeder used. Rather than list all characteristics here the reader is referred to vendor catalogues.

Care must be taken during installation to avoid pressure leaks, dents and discontinuities, all of which will affect the system performance. Professional experienced riggers are normally used with supervision by the equipment manufacturer. Foam filled coax is the easiest line to install but has higher loss than air dielectric.

The typical loss per hundred feet of several types of feeders is listed below:

At 950 MHz

	Loss per 100 feet
Foam dielectric (aluminum) coax:	
1/2 in. diameter	3.7 dB
7/8 in. diameter	2.0 dB
1-5/8 in. diameter	1.6 dB
Air dielectric coax:	
7/8 in. diameter	1.6 dB
1-5/8 in. diameter	0.8 dB

At 2 GHz

Foam dielectric (aluminum) coax:	
1/2 in. diameter	4.7 dB
7/8 in. diameter	3.4 dB
1-5/8 in. diameter	2.6 dB
Air dielectric coax:	
7/8 in. diameter	2.2 dB
1-5/8 in. diameter	1.3 dB

At 7 GHz:

Helical waveguide—Andrew type EW-59	1.5 dB
Rigid rectangular waveguide WR 137	1.8 dB

At 13 GHz

Helical waveguide—Andrew type EW 122	4.1 dB
Rigid rectangular waveguide WR 75	4.2 dB

PASSIVE REPEATERS

On some hops a passive repeater is used to clear an obstacle rather than an active repeater. The passive repeater may be either a billboard type or two parabolas back to back. The flat billboard type has an efficiency near 100 percent while the parabolas have an efficiency near 55 percent.

Because the gain of a passive repeater is proportional to the square of the frequency, their use is mostly limited to 7 and 13 GHz. The gain of a flat billboard is derived from Equation 5 as:

$$G = \left(12.77\, Af^2 \cos\frac{\theta}{2}\right)^2 \qquad [9]$$

where: A = Area of reflector in feet² (width X height)
f = Frequency in GHz
G = Gain in dB
θ = Angle between microwave beams extending to both adjacent stations.

Equation 9 is squared because the passive repeater has equal gain receiving and transmitting.

The performance of the hop may be calculated by considering 2 hops with a passive repeater with gain given in Equation 9.

When θ is too large to realize practical gain, a double billboard is often used, with one reflector illuminating the other. A loss of 3 dB is normally used for reflector—reflector coupling loss. The path is analyzed the same way as a single reflector except for the extra 3 dB loss.

For transmission calculations it is simpler to consider a single hop equal in length to the sum of the two legs extending to the passive repeater. In this case the passive repeater is considered to have a loss given by:

$$\alpha = \frac{2.9 \times 10^7\, d_1^2\, d_2^2}{(d_1 + d_2)^2\, f^2 A^2 \left(\cos\frac{\theta}{2}\right)^2} \qquad [10]$$

and in dB,

$$\begin{aligned} a &= 74.6 + 20 \log d_1 + 20 \log d_2 \\ &\quad - 20 \log (d_1 + d_2) - 20 \log f \\ &\quad - 20 \log A - 20 \log \cos\frac{\theta}{2} \end{aligned} \qquad [11]$$

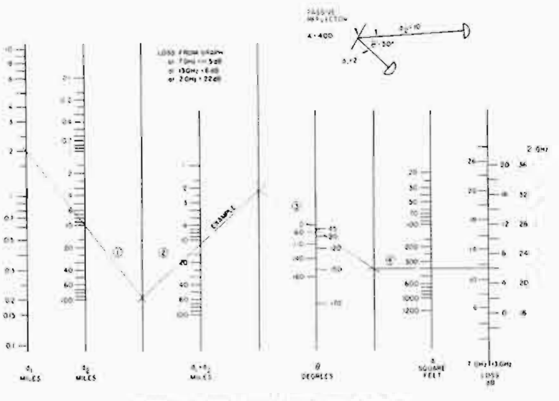
A solution to Equation 11 is given in Fig. 24.

When back-to-back antennas are used a coupling loss of 3 dB is included. To increase the gain of the two dishes a low noise TDA (tunnel diode amplifier) is sometimes used between the antennas. Performance calculations are best left to the manufacturer because of possible overloading of the TDA. The path is analyzed in the same manner using Fig. 24 as a passive repeater except the πr^2 area of the parabola used is multiplied by 55 percent efficiency, and $\frac{\theta}{2}$ is zero degrees.

The beam width of the flat billboard passive reflector repeater is given by:

$$\Upsilon = \frac{58.7}{fL} \qquad [12]$$

where: Υ = Beam angle in degrees
f = Frequency in GHz
L = Projected length of a side in feet (width X $\cos\frac{\Upsilon}{2}$)



PASSIVE REPEATER LOSS RELATIVE TO DIRECT TRANSMISSION OVER $D_1 + D_2$

Fig. 24. Passive repeater. (Courtesy of Microflect Corporation.)

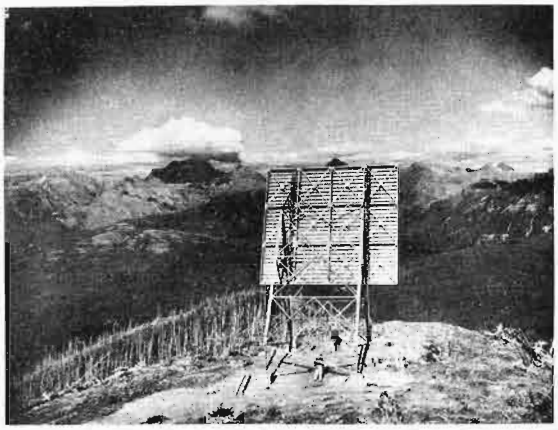


Fig. 25. Passive repeater loss nomogram relative to transmission over d_s and d_2.

Because the passive repeater does not require maintenance or operating costs, its use should not be overlooked when designing microwave systems. See Fig. 25 for a typical passive repeater 30 X 32 feet in area. Passive repeaters are available in a wide range of areas from about 8 X 10 to 40 X 60 feet.

PROPAGATION

Experimental work with microwave dates back to the 1930s, but it was not until about 1950 that practical systems were first installed. There are many modes of propagation: line-of-sight, diffraction, and scatter. Only line-of-sight will be discussed here.

Microwave propagation takes place in the first few hundred feet of the atmosphere which is called the troposphere. Many physical characteristics of the troposphere affect propagation, and it is well to discuss these characteristics before attempting to further investigate microwave propagation.

Free Space

Most discussions on propagation relate to a model which exists in free space with no obstructions and no tropospheric variations. Free space attenuation represents the loss between two isotropic antennas spaced at a distance d. The loss between two antennas is represented by the ratio of the power transmitted, P_t, to the power received, P_r. Referenced to isotropic antennas, the attenuation α may be derived from Equation 2 as:

$$\alpha = \frac{P_t}{P_r} = \frac{(4\pi)^2 d^2}{\Upsilon^{2}} \qquad [13]$$

In decibels,

$$\alpha = 20 \log \frac{4 \pi d}{\lambda} \qquad [14]$$

If λ is expressed as frequency (f) in GHz and d in statute miles the attenuation is:

$$\alpha = 96.6 + 20 \log f + 20 \log d \qquad [15]$$

At the three frequencies used by broadcasters a may be closely approximated by:

2 GHz

$$\alpha = 103 + 20 \log d \qquad [16]$$

7 GHz

$$\alpha = 114 + 20 \log d \qquad [17]$$

13 GHz

$$a = 119 + 20 \log d \qquad [18]$$

Equation 15 is used in the transmission calculations discussed later.

Fresnel Zones

In the early 1800s August Jean Fresnel, the French physicist, made important discoveries in the field of optics and in the wave theory of light transmission. Since microwave propagation is similar to light, his theories are used today by microwave engineers.

Fresnel established that the equivalent free space transmission energy seen at receiving point distant d from the transmitter is contained in an elliptical volume the size of which depends upon wavelength and distance. He further discovered that energy reflected to the receiver from points outside this volume reinforced or cancelled the energy from within the volume depending upon how far the reflecting points are outside the volume. By further experimentation he found that if the distance traveled by energy outside the elliptical volume is an odd number of one-half wavelengths longer than the direct distance between transmitter and receiver, the received signal was reinforced; but if the difference was an even number of wavelengths, the effect was cancellation. From his work, the concept of Fresnel zones was established.

The first Fresnel zone boundary is defined by a loci of points representing all possible paths one-half wavelength longer between transmitter and receiver than a straight line. The second, and interfering, Fresnel zone boundary is defined

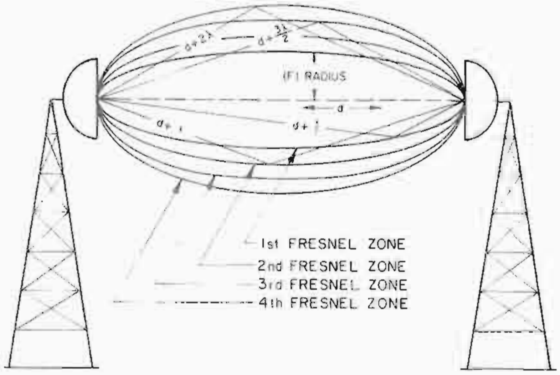


Fig. 26. Fresnel zones.

by path differences of one wavelength, the third by one and one-half wavelength, etc. This concept is shown in Fig. 26.

The microwave engineer is interested in the Fresnel zone radius at any point in the microwave path where there is an obstruction or highly reflective surface. If the obstruction blocks more than 40 percent of the first zone, attenuation will result, and if energy is reflected from an even number Fresnel zone, cancellation will occur. As the beam clearance is varied the signal will vary as shown in Fig. 27.

Because the microwave signal attenuation depends upon the situation in the Fresnel zones, it becomes necessary to determine the first Fresnel zone radius at any point along the path. By geometry the following equation is derived,

$$F = 72\sqrt{\frac{d_1 d_2}{fd}} \qquad [19]$$

where: F = First Fresnel zone radius—feet
d = Microwave path length—miles
d_1 = Distance from transmitter to point of calculation—miles
d_2 = Distance from receiver—miles
f = Frequency—GHz.

Other Fresnel zone radii can be calculated by multiplying Equation 19 by the square root of the Fresnel zone number. A nomographic solution to Equation 19 is shown in Fig. 27.

Diffraction

Francesco Grimaldi first noted and commented on light diffraction in a paper published posthumously in 1665. His work, followed by Newton and Fresnel, related the phenomena to wave theory in 1819. Fraunhofer classified the lines of the spectrum with a diffraction grating in 1821. If the ray theory is used, diffraction is the bending of rays over an obstruction due to Fresnel zone interference as discussed earlier. When an obstruction blocks all or part of the Fresnel zone, the energy received in the shadowed area is a function of the height of the obstruction and its shape. A sharp knife edge type obstruction blocks much less energy than a smooth sphere. These variations of received energy over different obstructions account for terms such as knife edge diffraction and obstacle gain. If the signal is diffracted over several successive obstacles the total loss is the sum of the diffraction losses over each obstacle. Fig. 27 may be used to calculate these losses.

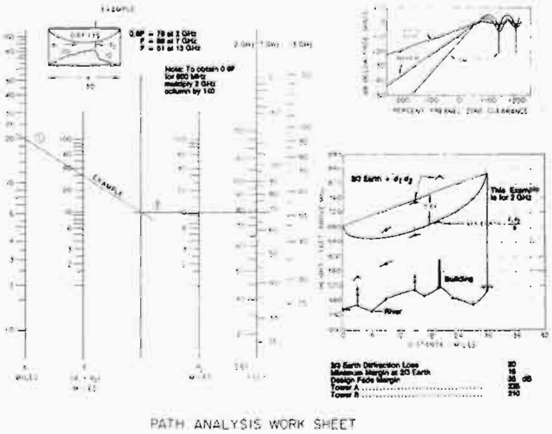


Fig. 27. Path engineering worksheet.

Refraction

The velocity of propagation is a function of the medium through which the wavefront of energy passes. In microwave transmission the useful wavefront may extend several hundred feet above the surface of the earth. The atmosphere or troposphere varies with height in density depending upon temperature, water vapor, and pressure. Normally the temperature, water vapor, and pressure decrease with height and the density also decreases. Thus the energy in the upper part of the wavefront travels faster than the lower and the energy between transmitter and receiver is refracted (bent) downward.

Under "abnormal" weather conditions, one or more characteristics of the troposphere might increase with height so that the microwave energy is refracted upward. Such a condition occurs fairly frequently when radiational cooling lowers the earth's surface temperature below that of the atmosphere above. This phenomenon is known as an inversion.

Occasionally, the characteristics of the troposphere might first decrease then increase and, finally, decrease again with height. Such conditions result in a propagation phenomenon known as ducting. Ducting is usually associated with weather fronts.

The degree of refraction varies with time of day and year and upon the weather at different geographic locations and elevations. Most of the time the microwave energy is refracted downward. Engineers have found it convenient to think in terms of straight beams or rays of energy propagated over a model earth with varying radius. Under normal tropospheric conditions, the energy beam can be thought of as straight if the earth's radius is increased to 4/3 true earth radius. For other conditions, true earth radius is multiplied by a factor K. Thus, we hear terms such as 4/3 earth, 2/3 earth, etc., as descriptions of propagation conditions.

When microwave energy is propagated over the earth, refraction affects the path clearance or degree of obstruction by the earth's surface. Over smooth flat earth the distance to the geometric horizon is given by,

$$d = \sqrt{\frac{3Kh_t}{2}} \qquad [20]$$

where: d = Distance to horizon in miles
h_t = Height of transmitting antenna in feet
K = Constant to account for degree of refraction.

Because K is normally 4/3 in microwave transmission, the horizon is extended beyond the geometric horizon obtained when K is equal to 1.

Under conditions of upper ducts or dense layers, microwave energy may be refracted strongly enough to appear as a reflection. This situation sets up Fresnel zone interference patterns. As the elevated layer moves up and down, the receiver signal strength varies widely as shown in Fig. 27. This condition is known as multipath fading.

Reflection

When microwave energy impinges on a smooth surface, it is reflected much as light is reflected from a mirror. When reflected, the energy undergoes a 180° phase shift such that it tends to cancel the directly received energy if the reflection is from even numbered Fresnel zones. Reflected energy from odd numbered Fresnel zones reinforces the directly propagated energy. The degree of cancellation or reinforcement depends upon the coefficient of reflection and shape of the reflecting surface. Reflection from a knife edge is nil, while reflection from the smooth earth covered with salt water approaches 100 percent efficiency. Most dry land surfaces with vegetation are considered rough; however, wet vegetation makes a good reflector. Reflection obeys Snell's law which states that the angle of reflection must equal the angle of incidence.

Absorption and Scattering

In the microwave spectrum below about 10 GHz, very little energy is absorbed or scattered by rain drops in the atmosphere. As frequency is increased above 10 GHz, the size of the rain drops becomes appreciable in comparison to the wavelength of the energy and significant absorption and scattering occurs. Fog, snow, and other similar tropospheric conditions do not absorb significant amounts of energy at frequencies below 13 GHz, although inversions and ducts accompanying these conditions might otherwise affect propagation.

The size of irregularities on the earth's surface affect the coefficient of reflection and degree of scattering. Likewise, the conductivity of the earth's surface affects the coefficient of reflection and degree of absorption. Thus energy impinging on a smooth sea or salt water flat is highly reflected, while energy impinging on a dry rocky surface is scattered and absorbed.

In the upper microwave frequency bands (above 10 GHz) the effect of absorption by rainfall must be considered. The following empirical formula can be used to estimate attenuation due to rainfall at 13 GHz.

$$a = 1.5Rd \qquad [21]$$

where: a = Attenuation due to rainfall
d = Distance along path covered by rain in miles
R = Rate of rainfall in inches per hour.

This formula is an approximation but can be used for design of 13 GHz systems.

Maximum rainfall rates vary widely with geographic location and along a path from one location to another. Average rainfall over a path of 10 miles may be only 40 percent that at a point of maximum rainfall rate in the path. Existing data show that for 0.01 percent of the time maximum rates of rainfall at a point vary with geography by 20 times from 0.25 in. per hour at Corvallis, Oregon, to 5 in. per hour at Miami, Florida. With such wide variations, it is difficult to give a rule-of-thumb for design purposes. If one designs for 0.01 percent annual rainfall outage on a 10 mile path, a maximum rainfall rate of 2 in. per hour will be adequate in most locations. A check with the local weather bureau might prove useful when designing 13 GHz paths.

Tropospheric Variations

For a fixed set of tropospheric conditions, prediction of the level of a received microwave signal is relatively easy using the principles discussed in foregoing sections. Unfortunately, the troposphere is a continually varying medium which in turn causes frequent variations in the level of the received microwave signal.

Standard conditions are defined by a well-mixed and turbulent troposphere with a negative height gradient (pressure, temperature, and water vapor) resulting in microwave beam curvature (refraction) equivalent to straight line transmission over an earth with a radius 4/3 times true earth. If the center of the microwave beam clears all terrain obstructions (allowing for 4/3 earth radius) by at least 0.6 first Fresnel zone radius, the microwave attenuation is equal to that in free space.

Tropospheric variations from standard vary with geography, time of day, time of year, and weather. Variations also occur from year to year. Dry and cool weather normally result in a standard troposphere at midday. Areas with prevailing strong winds have a standard troposphere most of the time. Standard tropospheric conditions prevail most of the time in areas with low rainfall (southwest US). Areas with heavy rainfall and/or wide variations of diurnal temperature often have a nonstandard troposphere with widely varying temperature, pressure and water vapor gradients with height—the southeastern US and Gulf Coast are typical of such areas. Prevailing weather conditions in the remaining areas of the US result in tropospheric conditions somewhere between the standard in the southwest and extreme nonstandard in the southeast and along the Gulf Coast.

Radiation cooling lowers the temperature near the earth such that the troposphere temperature rate of decrease at higher elevations is less than that near the earth. This reversal of standard temperature gradient conditions results in less refraction of a microwave beam toward the earth, and may result in refraction away from the earth when the temperature gradient is negative. During the same period of the year, the upper part of the troposphere may cool faster in the early evening hours than the earth's surface which was warmed during the day. This early evening upper elevation cooling increases the refraction of a microwave beam toward the earth such that the "radio horizon" is extended several times further than when standard conditions prevail. During the summer in many areas of the country, increased microwave refraction toward the earth (surface duct) occurs in the early evening followed by refraction away from the earth in the early morning. Both conditions can seriously degrade or disrupt microwave communications unless allowed for in the system design.

Weather fronts often result in nonstandard tropospheric conditions. Either refraction away from the earth or increased refraction toward the earth may result depending upon the type of weather front and prior weather conditions. For example, a warm front moving in over an area covered with snow can result in increasing temperature with altitude and refraction away from the earth. On the other hand a cold front can result in greater refraction toward the earth.

Elevated weather conditions occur at a frequency depending upon the geographic location. During these abnormal conditions, refraction may be standard near the earth, but substandard several hundred feet above the earth. Standard refraction near the earth results in normal line-of-sight microwave transmission, while super refraction high above the earth results in additional energy reaching the receiver which either adds or subtracts from the direct beam depending upon phase or difference in distance traveled. This condition is sometimes called an elevated duct.

Since the refraction gradient is a function of rate of change in pressure and water vapor as well as temperature and variation of these parameters is not always related to temperature in a constant matter, weather conditions other than those discussed can cause changes in the gradient. Since such changes are usually less severe than those discussed, special precautions are not usually necessary for these less frequent conditions.

The microwave transmission engineer should acquaint himself with weather variations expected in a given area and then make allowances for the extremes in his design. The degree to which varying tropospheric conditions degrade a microwave signal depends somewhat on the terrain of the earth as well as the weather.

Earth Terrain

Because microwave propagation occurs in the lower part of the troposphere, the earth's surface with or without irregularities affects the attenuation. Standard propagation conditions prevail relative to the effect of the earth, when the center of the microwave beam has adequate clearance over a rough and dry surface. The microwave transmission engineer must consider variations from this standard. A rough dry surface will absorb and scatter microwave energy, while a smooth reflective surface will act as a mirror.

The criteria for roughness is a complex problem which among other things is a function of wavelength or frequency of the microwave energy being propagated. In addition to roughness, the reflection coefficient of the surface is important. In microwave work a smooth sea is a good example of a highly reflective smooth surface—the Rocky Mountains are a good example of a rough, low-reflection area. As a rule-of-thumb, if the microwave beam passes over water, salt flats, desert or marshland, significant reflections are likely to occur. Whether or not such reflections affect propagation depends upon whether or not the reflected energy reaches the receiving antenna as determined by Snell's law and plane geometry. On the other hand, transmission over woodlands, mountains and farm lands does not usually produce surface reflections, which have a pronounced effect on propagation, unless there is dew or rain on heavy vegetation. Transmission in highly populated areas can be unpredictable because possible reflections from buildings, tanks, etc., can cause unexpected degradation of signal.

Another important variation from standard conditions is the shape of an obstruction in paths with less than 0.6 first Fresnel zone radius clearance. If the obstruction is a single mountain or building, attenuation is considerably less than when the obstruction is smooth earth or a series of mountains or buildings. In the first case, propagation occurs by diffraction over the single obstacle, while in the second case, propagation is supported by a series of diffractions and losses over each obstruction. The amount of attenuation is a function of the size of the obstruction relative to the Fresnel zone radius rather than the absolute size in feet.

When the center of a microwave beam clears earth terrain obstructions by more than 0.6 first Fresnel zone radius, the attenuation between the transmitter and receiver may be greater or less than standard depending upon both shape and reflection coefficient of the obstruction, as well as the amount of clearance relative to Fresnel zone radius. If the obstruction is knife edge and/or rough and nonreflective, the variation in attenuation as clearance is increased and is negligible, but if the surface is smooth and highly reflective, attenuation may vary in accordance with Fresnel's theory alternately from 6 dB less to infinitely greater than standard free space values.

Because of refraction in the troposphere, the effective clearance above obstructions may be more or less than that determined by absolute measurements. As discussed earlier, the effective clearance is normally greater than that measured over a true earth model because of downward refraction. Fig. 27 shows variations of attenuation from the free space model for smooth, average, and knife edge conditions as a function of beam clearance. For convenience, clearance is shown as a percentage of first Fresnel zone radius.

Fading

Variation of attenuation versus time is called fading. The foregoing discussions treat independently the various mechanisms and variations of propagation. In an actual installation, one, some, or all of these conditions may prevail independently or simultaneously. Fading is of two general types: multipath or earth bulge (below average refraction) and may exist independently or together.

Multipath fading is characterized by rapid variations in received signal level between stronger than standard and less than standard values. In general, the duration of these variations decreases with frequency, but the frequency of the variations increases with signal frequency. Interference results from either an out of phase reflected or refracted signal combining with the direct line-of-sight signal at the receiving antenna. Because the refractive index of the troposphere is constantly changing, the interfering signal alternates between reinforcement and cancellation of the directly propagated energy. At a given instant of time, fading (cancellation) may or may not occur depending upon frequency and receiver antenna location. Because effective path clearance either above the earth or below an elevated duct is a function of Fresnel zone radius and refractive index, a geometric layout and analysis of the transmission path will show the relationship with frequency and antenna location. When multipath fading is caused by reflected energy from the earth's surface, the depth of the fade depends upon the reflection coefficient of the obstruction; if it is caused by refracted energy from an elevated duct, the fade depth depends upon the refractive index. As a practical matter, depths may exceed 50 dB in severe cases, but are less than 40 dB in most cases.

There are several ways to combat multipath fading. These include frequency diversity, space diversity, or by greater fade margin obtained by increasing power, antenna sizes, or receiver sensitivity. If two microwave beams are propagated with a frequency difference of 4 percent or more, experience and calculations indicate that the signal level into both receivers rarely reaches a minimum at the same time. If two receivers with antennas physically located sufficiently far apart (usually vertically) are used, experience and calculations indicate that the energy from a single transmission beam rarely reaches a minimum at both receivers simultaneously. If a device (combiner or switch) is bridged arcoss the two receiver outputs, which constantly selects the strongest signal, either frequency or space diversity can significantly reduce interference fading. As the normal nonfaded received signal is increased above the minimum usable signal level (higher fade margin), the amount of time the system is disrupted is decreased. The approach or combination of approaches to multipath fade reduction is usually determined for each case and is a function of economics and the fading mechanism predicted.

Earth bulge (inverse beam) fading may be reduced by increased beam clearance or increased fade margin or both. Neither space nor frequency diversity has an appreciable effect on this type of fading. Increased beam clearance might increase multipath fading caused by reflections, and unfortunately, transmission paths with high earth bulge fading might also have high multipath type fading. Actual beam clearance is usually a compromise which is assisted with higher fade margins (40 dB or better).

High-low antenna techniques are sometimes effective for multipath interference fading caused by surface reflections and are of some value in earth bulge fading. This technique involves varying the height of the transmitting or receiving towers in order to shift the point of reflection. In general, if one antenna is high and the other low, fading of both types is minimized. If a transmission path crosses water located in the reflection zone, increasing the height of one tower and reducing the other will shift the point of reflection toward the lower antenna and in some cases to a zone of rough terrain which has a lower reflection coefficient. This technique is useful but not always feasible because of high cost or other restrictions on the higher tower.

For upper tropospheric layer refraction type multipath fading, optimum space diversity antenna spacing is not well understood, but the following equation, which assumes fading reflections, are from the second Fresnel zone, has proven satisfactory in many cases:

$$S = 25\sqrt{\frac{d}{f}} \qquad [22]$$

where: S = Spacing in feet
d = Path length in miles
f = Frequency in GHz.

Space diversity will often be necessary on over water paths, and spacing of only 25 percent that of Equation 22 will be helpful.

When transmitting over smooth terrain, multipath fading is often a result of interference from surface reflections. In this case, space diversity has proven very effective in reducing outage time. See Fig. 19 for an analysis of how to design this type of space diversity. Optimum spacing between antennas is given by,

$$S = \frac{1300\, d\,(\text{miles})}{h_T\,(\text{feet})\, f\,(\text{gigahertz})} \qquad [23]$$

If the spacing obtained from Equations 22 or 23 is not feasible because of economics, spacing of as little as 50 percent of the optimum value will be helpful. See Fig. 19 for explanation of Equation 23.

Fading Predictions

A statistical distribution attributed to the English physicist Lord Rayleigh is used widely in predicting fading outages in microwave systems. Multipath type fading follows the Rayleigh distribution. Fig. 28 shows the maximum amount of multipath fading anticipated for a given fade margin. Many measurements taken over the years show this value forms an outside limit for multipath fading in most areas, although in some areas fading time has exceeded that in Fig. 28. If adequately separated frequency or space diversity is used a minimum of 10 dB improvement is obtained, or outage time is reduced by about one-tenth—usually more.

In a system containing many paths in tandem, the probability of two paths fading simultaneously is small, but, of course, increases with the number of paths. In most practical systems, the total outage time of the system is equal to the sum of the outages for each path of the system. This summation applies to multipath fading only.

Earth bulge is characterized by long periods of low signal level and does not follow a Rayleigh distribution. In addition such fading might be in addition to multipath fading. Design precautions against earth bulge fading include a separate analysis of each path with an assumed re-

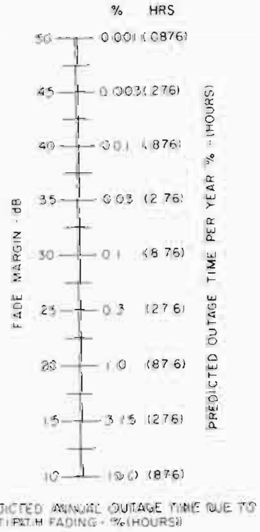


Fig. 28. Reliability versus fade margin.

fractive index equivalent to $K = 2/3$ or less in the southeastern US. From knowledge of the weather and type of obstruction in the path, one of the three height-gain curves of Fig. 27 may be used to determine maximum earth bulge fade depth. The fade margin should be at least 15 dB above the maximum expected earth bulge loss to allow for simultaneous multipath refraction from elevated ducts. Achievement of this fade margin might require larger antennas, higher towers, a shorter path, or a combination of all three.

PATH ENGINEERING

Path engineering consists of plotting the course of the microwave beam from one end of the system to the other including repeater stations, plotting elevation profiles for each path, station site selection, field survey, tower height calculations and a propagation analysis of each path to determine required fade margins. In many cases the path for an STL is short and little or no engineering is necessary. In others considerable time and analysis must be spent to insure reliable operation.

Map Study

The first step requires obtaining topographic maps for the area and locating all known stations. Aeronautical maps are useful for first approximations. Geological Survey maps are useful for map profiling. Using the maps, the microwave path is plotted and path profiles made including estimates for trees and man made obstructions. Towers are plotted to provide a minimum of 0.6 Fresnel zone clearance over 4/3 earth for 1 and 2 GHz systems, and full Fresnel zone clearance for 7 and 13 GHz systems. Trial and error methods are used until the most economical solution is obtained. In multihop systems, the hops should be zigzagged to avoid overshoot interference.

After the profiles are complete, a propagation analysis should be made to determine if the proposed solution will provide reliable operation. This analysis is described in the propagation section and shown in Fig. 27.

Field Survey

Before proceeding with station construction, the profiles are checked by a field survey. At the same time availability of land is checked. The field survey may be accomplished by hiring a land surveyor, or by the use of surveying altimeters which must be checked frequently against bench marks. If bench marks are not available known elevations can often be found on highways or railroads. Two altimeters are often used with one left at the bench mark with its reading recorded every 15 min or so for use in correcting the other unit being used on the microwave path. Complete instructions are included with the altimeter which may be purchased from American Paulin System, 1524 Flower Street, Los Angeles, California.

Fig. 27 is a work sheet including all information necessary to engineer and analyze the path. A supply of these sheets will be helpful throughout the path engineering project.

Most equipment manufacturers are prepared to contract for the path engineering task. Likewise, consulting engineers may be hired to do the task. The choice of do-it-yourself or by contracting is left to the broadcaster. In recent years the problem of obtaining the necessary permits for construction is the largest obstacle to building a microwave system.

Field Report

After the field work is complete an engineering report is prepared including survey notes, profiles, tower heights, site locations, and propagation analysis to determine desired fade margin. With this information the project is ready for system transmission calculations.

Propagation calculations may be made with the assistance of the work sheet in Fig. 27. The profile is plotted using any convenient scales. Controlling obstacles are adjusted for both 4/3 (normal) and 2/3 (abnormal) propagation conditions (see points at 9, 15 and 20 miles in Fig. 27). The first Fresnel zone radius (0.6 for 1 and 2 GHz) is calculated (use nomogram in Fig. 27) at each of these points. Antenna heights are selected to clear each obstacle by at least the required Fresnel zone radius. Next, the first Fresnel zone (0.6 for 1 and 2 GHz) is sketched as shown in Fig. 27. Under 2/3 earth conditions the clearance over each obstacle is determined in percentages of first Fresnel zone (8 percent at 15 miles and -30 percent at 20 miles in Fig. 27). From the loss curves in Fig. 27 using the average values, the loss at 15 miles (8 percent clearance) is 8 dB and at 20 miles (-30 percent clearance) is 12 dB which gives a total diffraction loss of 20 dB. If the rule of 15 dB margin above 2/3 diffraction loss is followed, a total fade margin of 35 dB is required in the example. The small loss due to the obstruction at 9 miles is ignored. If the frequency is at 13 GHz, the fade margin calculated should be modified to account for expected rain attenuation using Equation 21.

TRANSMISSION CALCULATIONS

After all path data are available, transmission calculations can be made to determine antenna size, type of feeders and any other equipment characteristics necessary to meet specified performance.

The basic transmission equation to determine fading margin is:

$$FM = P_T - (\text{Transmitter plus Receiver Coupling losses}) + G_T - a + G_R - \text{Field allowance loss} - P_R\ (\text{threshold}) \qquad [24]$$

where:

FM = Fade margin in dB
P_T = Transmitter power—dBm
G_T, G_R = Antenna gains—dB
a = Free space loss—dB
P_R = Improvement threshold power—dBm.

A solution to Equation 24 is given in Fig. 22 in a form which should greatly reduce the time for calculations. Completion of this work sheet will completely describe basic equipment characteristics and path performance. A supply of these work sheets will be helpful to the microwave design engineer.

The use of Fig. 22 is best explained by following through an example. From Fig. 27, the required fade margin for propagation reliability is 35 dB which is plotted on Column 1 in the nomogram. From the equipment curve in Fig. 22, threshold (32 dB S/N) occurs at a receiver input of -78 dBm, which is plotted on Column 2. Connecting these two points together gives the operating receiver input level in Column 3 (-43 dBm). From the equipment specification, the transmitter power is 2 watts, which is plotted in Column 5. By connecting Columns 3 and 5, the net path loss (NPL) is determined in Column 4 as 76 dB. This NPL represents loss between transmitter output and receiver input ports of the equipment. The frequency of the transmitter is plotted in Column 6 as 2 GHz. The path length in miles is plotted in Column 7 as 30 miles. Columns 6 and 7 are interconnected to intersect at a reference point on Column 8. This point on Column 8 is connected through the net path loss of 76 dB in Column 4 to a reference point in Column 9. The coupling losses are calculated in the table in the lower right corner of Fig. 22 as 9.7 dB and plotted on Column 10 of the nomogram. A line drawn from the reference point on Column 9 through the coupling loss on Column 10 will give the required product of antenna diameters (95) on Column 11. Thus two 10-ft. antennas are required.

Other sequences may be used to determine any unknown—for example, fade margin if antennas are known. In any sequence, plot all known values on appropriate columns. Draw lines to determine unknowns. Rather than use the work sheet in Fig. 22, some engineers prefer to tabulate Equation 24 as follows. The numbers shown are for the example in Fig. 22.

Free space loss (Equation 16, 17, or 18) 30 mi.	-132.6 dB
Feeder loss—transmitter	-2.7 dB
Feeder loss—receiver	-3.7 dB
Diplexer loss	-1.3 dB
Passive reflector loss/gain, transmitter	0 dB
Passive reflector loss/gain, receiver	0 dB
Field allowance	-2.0 dB
Total losses	-142.3 dB
Plus antenna gain, transmitter (10 ft.)	+33.4 dB
Plus antenna gain, receiver (10 ft.)	+33.4 dB
Net path loss	-75.5 dB
Plus transmitter power	+33.0 dBm
Receiver input level*	-42.5 dBm
Less receiver threshold	-78.0 dBm
Fade margin*	35.5 dB
Signal-to-noise (from equipment specification curve in Fig. 22)	62.5 dB

*One-half dB greater than Fig. 22 because two 10-ft. antennas are slightly larger than required from Column 11 of Fig. 29.

TELEVISION MICROWAVE EQUIPMENT TESTING

Microwave equipment is set up and tested in the factory as a system before shipment. All values specified are checked and equipment is adjusted for best performance. After installation all tests are redone on an over-the-air system basis. Since operating procedures for microwave equipment from different manufacturers varies, the instruction book should be referred to for specific setup and testing procedures. In addition to the brief measurement discussions presented here, the reader is referred to instruction books for the test equipment used for detailed information on method measurement.

Initial Setup

Before performing individual tests, a preliminary checkout and readjustment is advisable. To perform this test, the transmitter and receiver of each hop are connected together through an attenuator to simulate over-the-air transmission path loss (NPL)—an attenuation value of 70 dB or less is normally used in the factory, but the value calculated in Fig. 22 may be used for the field check. The attenuator should be variable up to 115 dB to check the threshold performance of the receiver. A waveform generator (Telechrome 3508 or equivalent) is connected to the input of the microwave transmitter in the system. A waveform monitor (Tektronix 529, or equivalent) is connected to the output of the microwave receiver (to preserve correct termination, check that the waveform monitor is terminated in 75 ohms). See Fig. 29 for test setup. The following procedure is followed:

1. Connect transmitter to receiver through attenuator pad (70 dB);
2. Connect main power to equipment and turn on;
3. If the microwave is built for multiple frequency operation, turn channel selector switches on transmitter and receiver to same channel;
4. Connect test equipment as shown in Fig. 29;
5. Compare meter readings on both transmitter and receiver with factory test data sheet;
6. Check receiver discriminator meter reading, and, if necessary, adjust transmitter frequency for zero meter reading (use internal receiver meter);
7. Set waveform generator for window signal and adjust level for 1-volt sync peak to window peak signal as observed on waveform monitor;
8. Check transmitter power output using internal meter reading or external power meter for same value as on factory test sheet;
9. Check and adjust if necessary transmitter FM deviation, using procedure in microwave equipment instruction book;
10. Check receiver sensitivity by noting that the AGC meter reading is the same as factory test data sheet for 70 dB path loss;
11. Check receiver signal outputs (usually two) for 1.0 volt output on waveform monitor—adjust if necessary; and
12. Vary attenuation between transmitter and receiver and note that AGC meter reading in receiver agrees with factory test data sheet.

Multiburst Test

The multiburst signal is used to observe the medium and high amplitude—frequency characteristics of the system. The signal generator (Fig. 29) is set for a multiburst output which consists of a peak white pulse (1.0 volt from sync peak to pulse peak) called the white flag, followed by six sine-wave bursts at frequencies of 0.5, 1.5, 2.0, 3.0, 3.6, and 4.2 MHz. This series of signal bursts are observed on the monitor for one horizontal line interval (62 microseconds or at a 15.750 kHz rate). While the multiburst signal is not a complete check on frequency response, if all bursts are within two to three percent of the one volt reference, the equipment is functioning properly with a medium and high frequency response within 0.2 to 0.3 dB of reference value. See Fig. 30 for a typical waveform, and see Fig. 31 for a waveform at the output of a system with a rising frequency response.

Window Signal

With the waveform generator of Fig. 29 set at window signal a good check on several system characteristics may be made, including:

1. Level check—peak-to-peak signal level (usually 1 volt);
2. Observation of low frequency response by checking tilt (roll off) of the window signal. Waveform monitor should be set for two field observations, tilt should be 1 percent or less of the 1 volt reference signal. See Fig. 32;
3. Ringing check (transient response) measured by observing the amplitude of any oscillation following rise or fall of the window signal pulse. The amplitude of such ringing is usually less than 2 percent in a good microwave system; and
4. System low frequency hum measured by observing the amplitude of low frequency modulation on the two field window signal as a percentage of reference level of 1 volt. In a good system, hum level is less than 0.5 percent and is not noticeable on the waveform monitor. (See Fig. 32.)

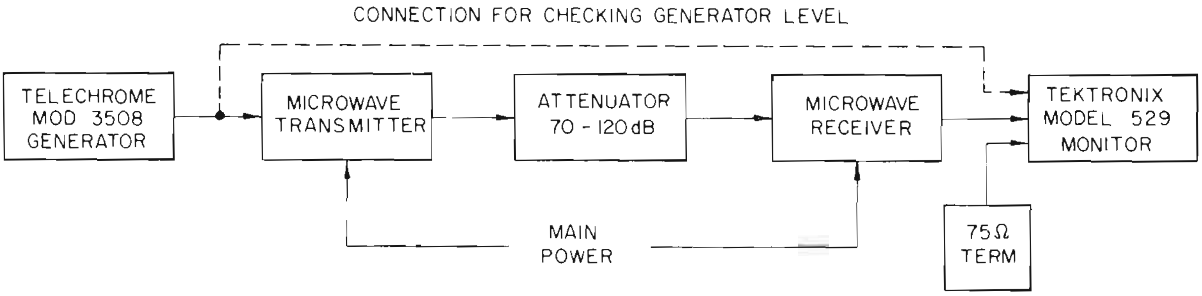


Fig. 29. Test setup for initial checkouts. Differential gain and multiburst measurements.

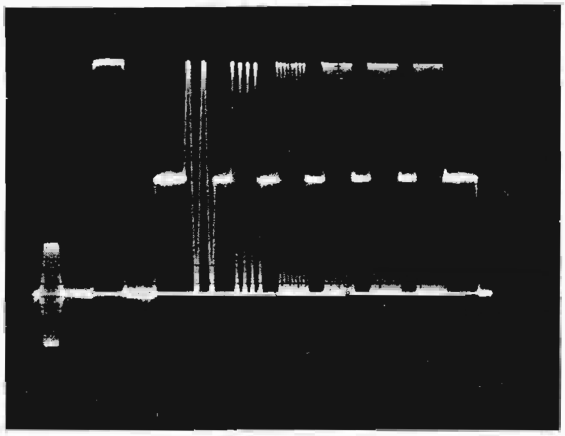


Fig. 30. Input multiburst signal.

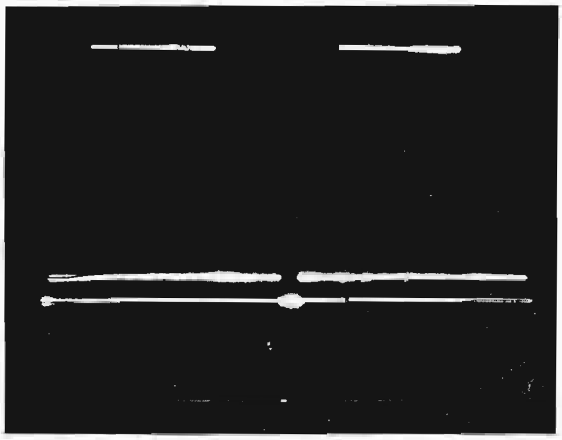


Fig. 32. Two field window signal.

Pulse and Bar Test and Transient Response

The transient response of the microwave system is important to prevent ringing of the video signal and resultant multiple echo effects on the picture. It is measured by using the pulse and bar test, which consists of a modified window signal plus a $\sin^2$ pulse (see Fig. 33). The $\sin^2$ pulse has no significant energy content above a frequency equal to $1/T$ (where T equals width of pulse at mid amplitude). Since the leading and trailing edge of the bar have a rise and fall equal to the $\sin^2$ pulse, it too has low energy content at frequencies above $1/T$. The pulse and bar input signal is obtained from the waveform generator (see Fig. 29), and the pulse for a 4 MHz system may be either a T pulse 0.125 microseconds or a $2T$ pulse 0.250 microseconds as measured at its 50 percent amplitude. The T is equal to $\frac{1}{2F}$ where F is equal to the highest frequency of the system—about 4 MHz for an NTSC system.

The pulse and bar test is an important measurement because the bar gives a good indication of high frequency performance. Poor low frequency response will show up as tilt of the bar and poor high frequency response will show up as decrease in amplitude of the pulse and increase in pulse width. Phase distortion in the system will show up as skewing of the pulse. Poor transient response will be observed as ringing on the trailing edge of the pulse and on the peak of the leading edge of the bar as well as the bottom of the trailing edge of the bar. The $2T$ pulse (energy up to 2 MHz) gives an evaluation of the lower frequencies (0.5 to 2.0 MHz) in the system, while the T pulse gives an evaluation of the upper frequencies (2.0 to 4.0 MHz). Fig. 34 shows a system oscillogram for a $2T$ pulse at the output of the microwave receiver in a system with good transient response.

To assist in evaluating the transient response of the system, a special graticule is available for the waveform monitor which outlines an envelope into which the pulse must fit (see Fig. 34). Along the baseline, two envelope limits are included:

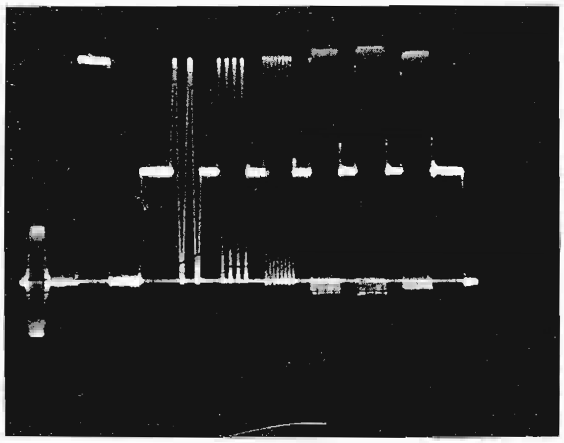


Fig. 31. Output multiburst signal with rising frequency response.

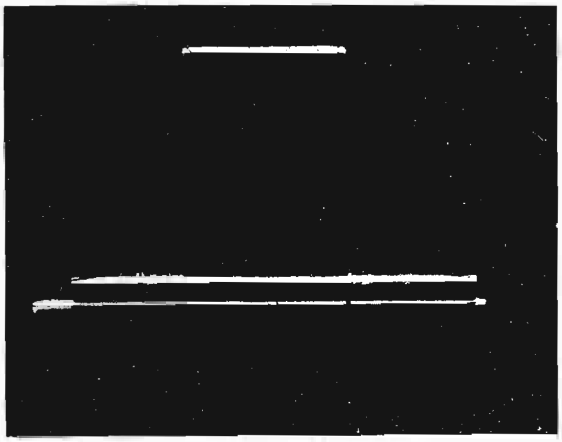


Fig. 33. Pulse and bar signal.

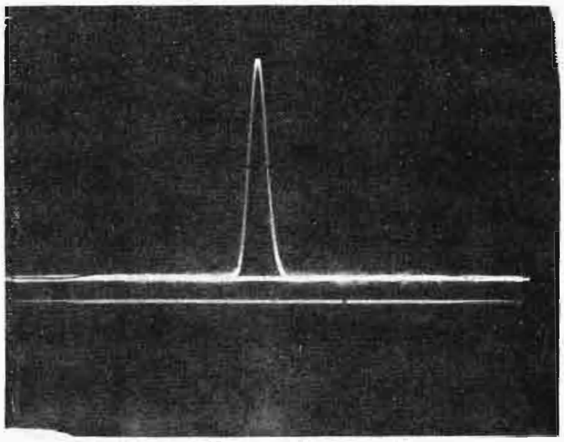


Fig. 34. System output 2*T* pulse (250 microsecond).

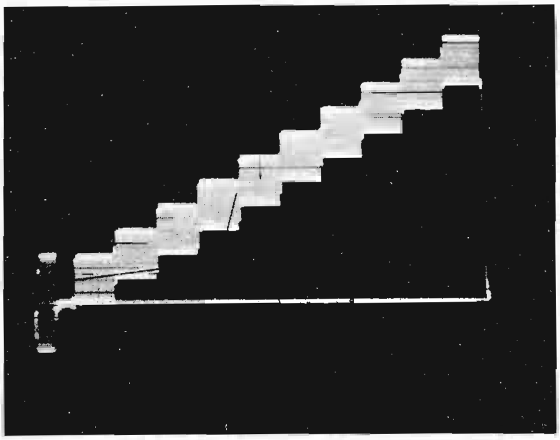


Fig. 36. Stairstep signal plus 3.58 MHz subcarrier.

one representing a 2 percent ringing and the other a 4 percent ringing, which represents the maximum allowable amplitude of the ring as compared to the pulse.

The test is usually made with a 2*T* pulse but for good microwave systems the *T* pulse ringing will also stay well within these limits, and the 2*T* pulse ringing will not exceed 1 percent. The results of these tests are called the *K* factor which is specified as 1 percent, 2 percent, etc. See Fig. 34 for a normal *T* pulse at the microwave receiver output.

The pulse and bar test is especially useful for giving a quick overall check on most important characteristics of the microwave system. With experience, maximum information regarding frequency response, phase distortion, and transient response may be determined.

Differential Gain

Differential gain at 3.58 MHz (color subcarrier frequency) is important in a color TV transmission system because excessive differential gain will cause changes in amplitude of the 3.58 subcarrier as the luminance signal varies from black to peak white. Differential gain is measured by transmitting a stairstep signal through the system. It is called stairstep because the change from black to white is effected by 10 step changes in level. See Fig. 29 for test setup and Fig. 35 for an oscillogram of the stairstep.

System linearity may be quickly checked by noting whether or not the steps as viewed on the waveform monitor at the receiver output are all of equal amplitude. To measure differential gain, the stairstep signal is modulated with a 3.58 MHz signal (see Fig. 36). Differential gain at 3.58 MHz is measured by determining the maximum difference in level of the 3.58 MHz modulated signal between the various 10 steps of the stairstep signal. For convenience in measurement, the receiver output is connected through a low pass filter in the waveform monitor which removes the stairstep and leaves only the 3.58 MHz subcarrier. Differential gain is determined by noting the difference in amplitude of the subcarrier bursts as viewed on the waveform

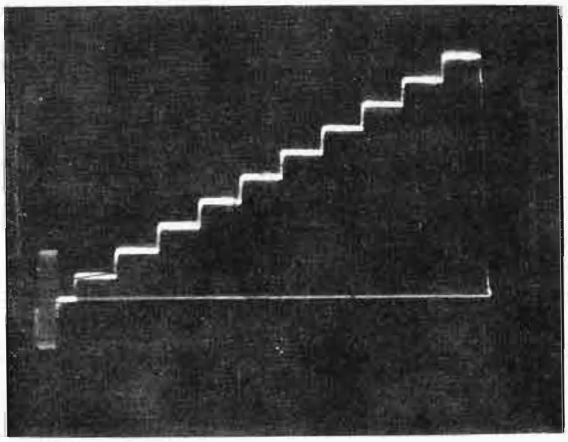


Fig. 35. Stairstep signal (no modulation).

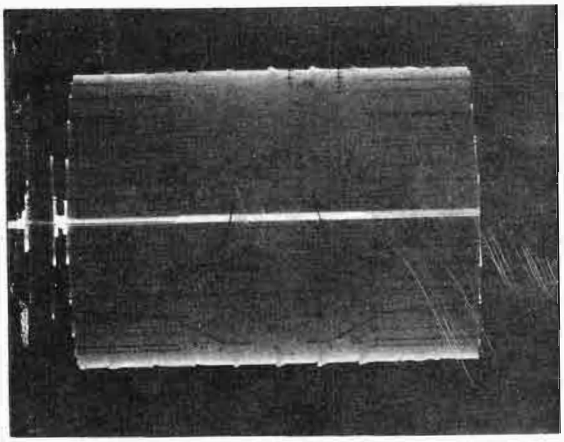


Fig. 37. Differential gain measurement at 50 percent APL.

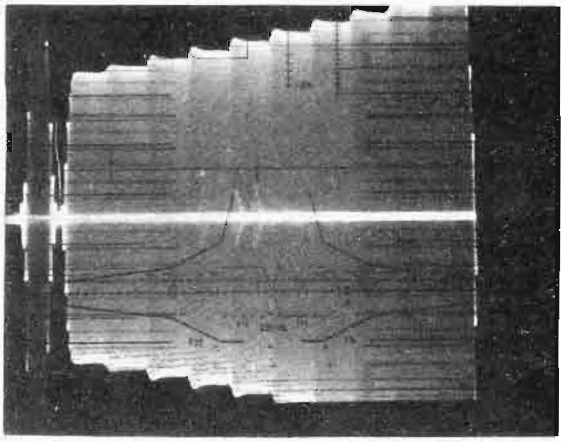


Fig. 38. Excessive differential gain at 50 percent APL.

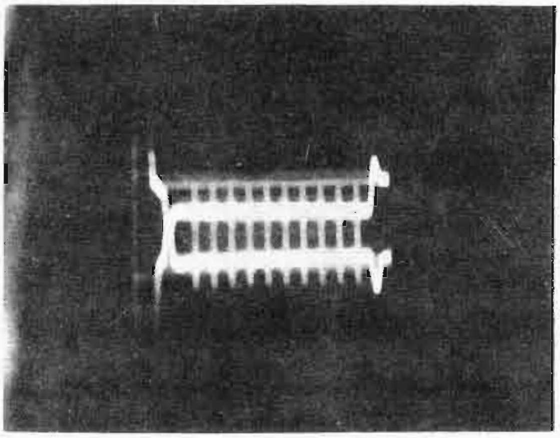


Fig. 39. Differential phase (0.6 degrees).

monitor. See Fig. 37 for an oscillogram from a good system and Fig. 38 for an oscillogram from a system with almost 10 percent differential gain.

Differential gain is usually specified at 10 percent, 50 percent, and 90 percent APL (average picture level). These measurements are made as discussed above with the waveform generator set in turn to each of the picture levels. Fig. 38 is 50 percent APL.

Differential Phase

Differential phase affects hue of the color picture and represents changes in phase of the 3.58 MHz subcarrier as video luminance level changes from black to peak white. It is measured by transmitting the stairstep signal from the waveform generator plus 3.58 MHz subcarrier through the system. Differential phase is measured using a phase detector built into a vectorscope (Tektronix 520) to compare the phase of the waveform generator reference signal with the phase of the 3.58 MHz subcarrier signal transmitted through the system on the stairstep. The test setup in Fig. 29 is used with the high impedance vectorscope connected in parallel with the waveform monitor. Differential phase is measured directly in percentages on the waveform monitor by noting a dial reading corresponding to phase adjustment of the reference signal to zero out the differential phase of the transmitted signal as viewed on the vector scope. Fig. 39 is an oscillogram with excessive differential phase.

Differential phase is measured at 10 percent, 50 percent, and 90 percent APL. It should be less than 0.5° at all picture levels.

Video Signal-to-Noise

Video signal-to-noise is measured as the ratio in dB of peak signal level (usually 1 volt) to rms noise. The test setup for measuring signal-to-noise is shown in Fig. 40. Note that low frequency noise is attenuated by the EIA filter and hum reject filter. To make the measurement, first check that gain through microwave system is unity (1 volt input and output), and then measure rms value of noise on the voltmeter. Signal-to-noise is determined from 20 log of the ratio of peak signal to rms noise voltage. The value of signal-to-noise usually exceeds 60 dB.

Equipment Gain

To determine the equipment gain or maximum net path loss of the equipment (approximately 78 plus transmitter power in dBm for most systems) the value of the path attenuator should be increased until the S/N decreases to 32 dB (minimum acceptable value). Use of MTA (microwave transistor amplifier) or TDA (tunnel diode amplifier) will result in 4 to 5 dB improvement

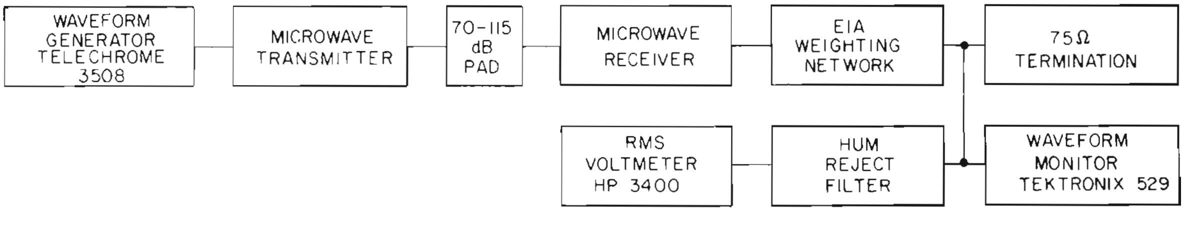


Fig. 40. Test setup for measuring video signal-to-noise.

in receiver threshold. The amount of attenuation used to obtain 32 dB S/N is the equipment gain figure.

Video Signal-to-Hum

This measurement represents the ratio in dB between peak signal level (usually 1 volt) and peak hum level. The test setup in Fig. 29 is used except a low pass hum filter is inserted ahead of the oscilloscope. Although the Tektronix 729 Waveform Monitor may be used for this measurement, the sensitivity is not adequate for a precise observation. It is recommended that any high gain oscilloscope be used in place of the waveform monitor for this test. With the waveform generator disconnected the peak-to-peak hum level is observed on the oscilloscope. The video signal to hum ratio in dB is calculated from 20 log (ratio p-p signal to p-p hum). Typically the ratio exceeds 46 dB.

Audio Channel Measurements

The audio channel (TV or 950 STL) frequency response is measured by the point-to-point method using an audio signal generator at the input and an rms voltmeter at the output of the system. The response from 50 Hz to 15 kHz should be better than specified in EIA Standard RS 250A.

The audio channel signal-to-noise is measured using a HP 650 generator set at rated level at the input of the transmitter and an HP 3400A rms meter at the receiver output. For an audio channel transmitted on a subcarrier above video, a window signal should be transmitted through the video channel to simulate actual operating conditions which can result in crosstalk from video to audio channels. The audio signal-to-noise should exceed 60 dB, including any crosstalk from the video signal, in most microwave systems.

The audio channel distortion is measured by connecting a signal generator (HP 650A) set for rated level to the transmitting input and a distortion meter (HP 333A) connected at the receiver output. With the transmitter set for rated modulation, the receiver is set for rated output level. The distortion meter (set at the measuring frequency) reads total harmonic distortion. Measurements are made at frequency intervals between 50 Hz and 15 kHz (see EIA RS 250A). Distortion in most systems will not exceed 1 percent at all frequencies.

While making all audio measurements, the use of correct terminating impedances should be strictly observed. Experience shows that the most frequent problem with audio measurements is incorrect termination—follow test equipment instructions carefully.

MULTIPLE HOP MEASUREMENTS

After the equipment has been checked in accordance with the aforementioned procedures on a per hop basis, it is then connected together as a system and rechecked on a systems basis. For multiple hop systems the procedure as given previously cannot always be followed on a hop-by-hop basis because the repeater equipment may not have audio/video separation equipment or pre- and deemphasis circuits. For these reasons multiple hop systems may have to be checked directly on a systems basis without performing the per hop test. Each situation will have to be decided on its own merits, and close adherence to the manufacturer's test instructions is recommended. During the multiple hop test at least the RF characteristics of the microwave equipment at each repeater should be checked by varying a path loss attenuator to determine receiver sensitivity and equipment threshold characteristics. The S/N of a multiple hop system is usually degraded by 10 log *n* dB from the single hop S/N, where *n* is the number of hops. Likewise other characteristics such as frequency response, diferential phase, and differential gain may also degrade on a 10 log *n* basis. It is common practice to recheck the multiple hop system on an end-to-end basis after installation is complete.

MAINTENANCE OF MICROWAVE SYSTEMS

Along with the trend to all solid state systems maintenance procedures have changed completely during the past few years. Previously system reliability depended heavily upon frequent maintenance checks and logging of various meter readings from which many tube failure predictions could be made. From records of these preventive maintenance checks, vacuum tubes were replaced and equipment realigned as necessary. In many systems preventive maintenance was required on a weekly basis.

Since the advent of solid state equipment, preventive maintenance checks have been dropped from the operating procedures. The broadcaster keeps an adequate supply of spare modules as recommended by the manufacturer. In the event of equipment failure the faulty module is isolated quickly using built-in metering. It is then replaced by a spare module, and in well-designed systems no realignment is required. The faulty module may be repaired either at the broadcaster's repair facility or may be returned to the manufacturer. The latter practice is recommended because the manufacturer is more experienced and better equipped to restore the faulty module to its original performance characteristics than the broadcaster. Field experience shows that the cost of spare modules for today's solid state equipment is much less than the cost of maintenance technicians for yesterday's tube equipment.

Most equipment in a microwave system other than electronic gear, such as towers, antennas, feeders, power supplys, etc., requires very little maintenance. In the case of towers and lighting, the FAA has certain requirements regarding painting and observation that the tower lights are working. The reader is referred to the FAA Rules and Regulations for more detail on this requirement.

The reliability and life of solid state equipment is somewhat dependent upon the operating temperature and the variation between temperature extremes. Investment in air-conditioning equipment can be economically justified on the basis of fewer equipment problems. In most areas, the low temperature extremes are not severe enough to require heating in the winter except for the comfort of any personnel who may be working in the area.

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