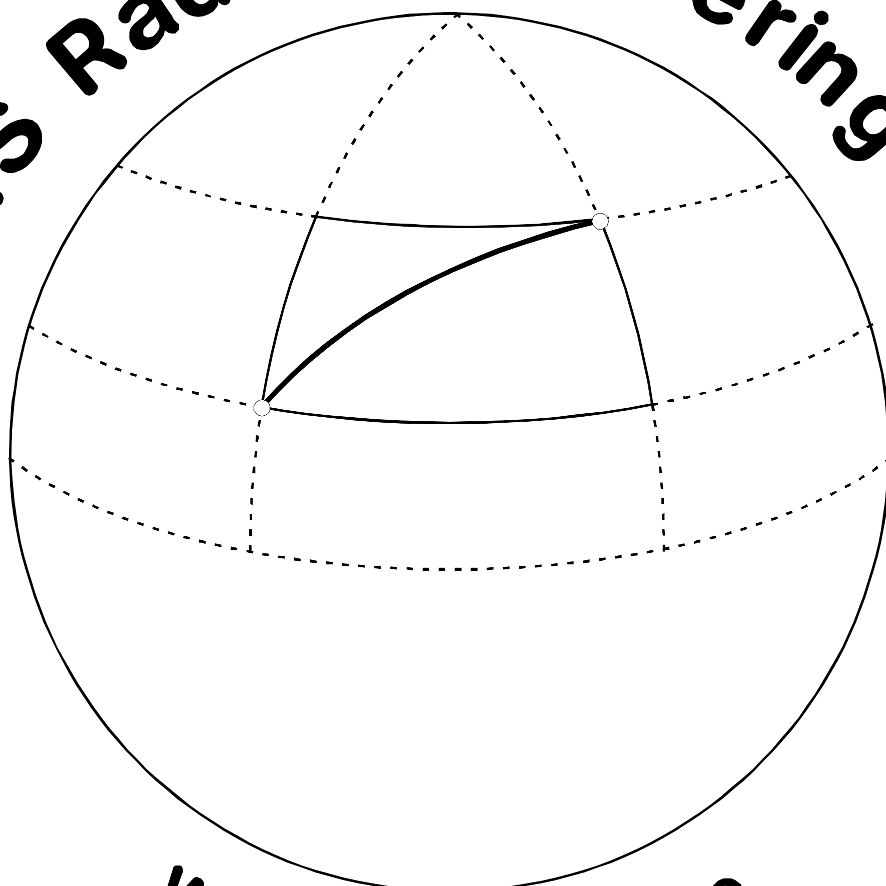
BETRS Radio Engineering Guide



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BETRS Radio Engineering Guide

Notice: This guide originally was written for internal company use in 1993 and updated in 1998. It has not been updated since that time and some sections are out-of-date or obsolete. This guide was made publicly available for historical purposes in 2013.

B E T R S R a d i o E n g i n e e r i n g G u i d e

Preface

This guide is written for practitioners in the field of radio communications and has special emphasis on the application of Basic Exchange Telecommunications Radio Service (BETRS) systems in Alaska. Many of the characteristics so described apply in many other parts of the world (except tropical areas) because Alaska is so large and has such a varied climate and topography.

This guide assumes the reader has a basic knowledge of algebra, radio-wave propagation and the technical and regulatory requirements for installing and using radio systems. The reader is cautioned to abide by all federal, state and local electrical codes, rules and regulations, and to follow industry practices, and to use common sense when applying this information.

This guide does not provide professional engineering advice. Readers shall use the information contained herein at their own risk. This guide is provided solely for the reader's consideration and study and includes no claim whatsoever as to accuracy of content or information. The author specifically disclaims all warranties, expressed or implied, including, but not limited to, merchantability and fitness for a particular purpose. In no event shall the author be liable for any loss or damage, and for personal injury, including, but not limited to, compensatory, special, incidental, consequential, or other damages.

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1. Introduction

The *BETRS Radio Engineering Guide* primarily covers the considerations necessary for proper engineering of Basic Exchange Telecommunications Radio Service (BETRS) systems. Subjects covered include regulatory aspects, frequency bands, propagation, modulation, transmitter and receiver performance, antennas and supporting structures, coaxial cables, grounding, quality of service and traffic considerations, computerized path analysis, installation considerations and tests and measurements. Several appendices are provided which cover the actual frequencies involved, a table of transmitter and receiver performances, antenna tower foundations, site surveying, position and distance calculations and a list of PC compatible path analysis software vendors.

The BETRS Radio Engineering Guide does not cover co-channel interference nor does it cover FCC licensing procedures, both of which are covered in monographs to be published separately.

Two types of systems are used in BETRS – point-to-point and point-to-multipoint. A point-to-point system serves only one subscriber (using one frequency pair) while a point-to-multipoint system serves multiple subscribers with one or more frequencies.

From a propagation standpoint, the engineering of point-to-point and point-to-multipoint (trunked) systems is identical. However, point-to-point systems normally are engineered on a *path* basis while point-to-multipoint systems are engineered on a *coverage* basis. This guide does not differentiate between these two; instead, it discusses a number of propagation path models, which apply to both point and multipoint systems equally. The various path models are of summary interest and are provided as a basis for computerized path analysis, which normally is much more accurate, convenient and faster.

The present BETRS market for multipoint systems is highly focused because only two manufacturers build multipoint systems - one analog FM and one digital. A number of manufacturers build analog point-to-point systems.[1] For the most part, these market limitations do not affect the radio engineering process; where they do, specific information is provided in this guide.

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[1] At the time of this writing (late 1994) there was only one manufacturer of analog multipoint systems designed specifically for BETRS applications (Carlson Communications - *OptaPhone STAR*) and one manufacturer of digital multipoint systems (InterDigital Communications - *UltraPhone*®). One other manufacturer of digital BETRS multipoint systems closed down its product line in 1993 (Alcatel - *CXR-424*). A number of manufacturers currently make analog point-to-point systems including Carlson Communications – *OptaPhone Plus*, Telepoint *RTL-1000*, Datacom *Phonelink*, and Telemobile. The E.F. Johnson LTR™ trunked radio system, which is based on analog FM, has been adapted for BETRS by at least one local exchange carrier in Alaska and the Glenayre IMTS system, which also is based on analog FM, is used by at least two local exchange carriers.

2. Regulations

The Basic Exchange Telecommunications Radio Service is covered by the Public Mobile Service regulations of Federal Communications Commission (FCC) Part 22, Subpart H, Rural Radio Service. Subpart H refers to other subparts of Part 22, so it does not completely stand alone. Thus, in order to understand the Rural Radio Service and BETRS, it is necessary to understand most of Part 22 (easier said than done and the subject of a separate monograph).

All present BETRS *systems* require an FCC license (transmitter authorization) at the central office station. There is no exception to this requirement in spite of what some BETRS equipment sales people have told potential buyers.[2] BETRS stations normally are licensed by the local exchange carrier but systems or stations may be licensed by individuals, as well, provided the individual meets the eligibility requirements of the FCC regulations. While licensing is beyond the scope of this guide, the reader should realize the very high risk and liability that goes with operating a BETRS system without a license.

The *central office station* is defined by the FCC as "A fixed station used for transmitting communications to rural subscriber stations associated therewith." It basically is the base station equipment, which usually is installed in or near the central office. However, it is not necessary to install this equipment at the central office; it may be installed at a remote location (for example, a hilltop). As would be expected, a *rural subscriber station* is "A fixed station in the Rural Radio Service used by a subscriber for communication with a central office station." The terms central office station and subscriber station are used frequently in this guide.

In addition to the FCC rules, the National Electrical Code (NEC) and National Electrical Safety Code (NESC) apply in most situations.[51, 52] Installations on subscriber premises must comply with NEC Articles 800 and 810, and utility owned poles and supporting structures must comply with the NESC. While most central offices are exempt from the NEC, installations in them should comply with NEC requirements, nevertheless.

Both the NEC and NESC are adopted by State of Alaska and enforced by the Department of Labor. Individual communities may adopt the NEC and NESC and, in some cases, may amend specific requirements. In addition, the Alaska Public Utilities Commission (APUC) regulates local exchange carriers (LEC), which own and operate many BETRS systems. The FCC rules allow private individuals to own and operate BETRS systems within the framework of the Rural Radio Service.

The APUC has no direct regulatory oversight of BETRS, and requires no separate certification, provided the systems are deployed within the local exchange carrier's (LEC) certified service area. It is not necessary that BETRS be offered by an LEC under a separate tariff or rate structure. It is common for potential BETRS subscribers to be beyond an LEC's service boundaries. In such cases, the LEC

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[2] As the demand for Personal Communication Services (PCS) expands into rural areas and low cost base station equipment is developed based on spread spectrum modulation techniques, it is entirely possible future BETRS may be offered through unlicensed base stations; however, such equipment is not now available.

must amend its service area to include that subscriber or request a waiver of the APUC regulations that prohibit an LEC from serving subscribers outside of its authorized service area.[3]

Prior to 1985, the FCC had specific licensing requirements for people who operated and maintained commercial radio transmitters. Basically, a 2nd Class Radiotelephone Operator License was required for radio transmitters other than broadcast, and a 1st Class Radiotelephone Operator License was required for broadcast. However, in 1985 the FCC revised the license requirements and the 1st and 2nd Class licenses were replaced by the General Radiotelephone Operator License. This license is now required only to operate (and maintain) stations used in the Aviation, Marine and International Fixed Public Radio Services.

Licensing requirements for commercial radio operators are contained in FCC Part 13, Commercial Radio Operators. This part contains no provisions for an operator license in the Basic Exchange Telecommunications Radio Service. Nevertheless, certain organizations have undertaken to replace the previously required FCC operator licenses with various types of technician certifications. While these certifications are not yet officially required by the FCC rules, many companies in the radio communications industry require their technicians obtain them. Of particular interest to people working on BETRS systems is the National Association of Radio and Telecommunications Engineers (NARTE), which offers both technician and engineer certifications.[4] Even though operator licenses are not required for BETRS systems, all station licensees are obligated to know and understand Part 22 and other applicable rules.

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[3] AS 42.04.221 prohibits an LEC from providing service outside the scope of its certificate of public convenience and necessity. Since the certificate includes a description of the LEC's authorized service area, serving subscribers outside the area clearly is outside the scope.

[4] NARTE, P.O. Box 678, Medway, MA 02053, Tel. 800-89-NARTE.

3. Frequency Bands

There are three frequency bands available to BETRS. These are nominally 150 MHz, 450 MHz and 800 MHz. The actual frequencies are listed in Appendix A. Most BETRS systems operate in the 150 MHz VHF and 450 MHz UHF bands. In Alaska, there is at least one system operating in the 800 MHz band. This guide is primarily concerned with the 150 and 450 MHz systems, although the propagation characteristics described also apply to 800 MHz systems.

Table 1 compares the important characteristics of the different frequency bands. In this table, the receiver noise refers to the general effects of internal and external noise on the receiver. The 150 MHz band generally is susceptible to external noise including atmospheric and galactic noise and locally generated noise due to ignition systems and other radio systems operating in the VHF band. Receiver low signal level performance is limited by these external influences, and users will notice this noise when the system is operated in a fringe area. In areas of considerable VHF radio activity and industrial activity, the noise floor is raised. To obtain the same signal-to-noise ratio, the received signal levels must be higher. The two higher bands, 450 and 800 MHz, normally are not affected by external noise, but the receiver performance is limited by self-generated (internal) thermal noise in the receiver front-end.

Table 1
Frequency Band Comparison[5]

Characteristic	150 MHz Band	450 MHz Band	800 MHz Band
Relative free-space loss	0 dB (reference)	9.4 dB	14.7 dB
Relative antenna dimensions	Largest (3 ft)	Medium (1 ft)	Smallest (½ ft)
Receiver noise	Affected by atmospheric noise and local noise sources	Internal receiver noise limited	Internal receiver noise limited

BETRS frequencies are allocated in pairs. For a given transmit frequency at the central office station, there is a corresponding, but off-set, transmit frequency at the remote subscriber station. That is, if the central office station transmits on frequency f_1 and receives on frequency f_2, the subscriber station receives on f_1 and transmits on f_2. By having different transmit and receive frequencies, the pairing allows full duplex transmission.

The frequency off-set between the two transmitter frequencies in the pair is approximately 5 to 6 MHz in the 150 MHz band, exactly 5 MHz in the 450 MHz band, and exactly 45 MHz in the 800 MHz band. The offset is necessary because of equipment technical limitations. The nominal free-space wavelengths and approximate physical lengths of half-wave dipole antennas are given in Table 2 for each band.[6] The free space wavelength **λ** can be found from

[5] The relative free-space loss in this table indicates the effects of frequency on propagation. Using the 150 MHz band as a reference, a system operating in the 450 MHz band will have 9.4 dB more loss. This additional loss is inherent and unavoidable. In some installations, the physical size of the antenna is a critical issue. The tables shows that a system operating in the 450 MHz band will have about 1/3 the physical dimensions of a system operating in the 150 MHz band.

[6] The physical length of a half-wave dipole is 4% to 5% shorter than the free-space half-wavelength.

$$\lambda = \frac{c}{f} \tag{1}$$

where c = velocity of light in a vacuum and f = frequency in Hz. The velocity of light is 3E8 m/s, which gives the wavelength in m.[7] For wavelength in ft, use 984E6 ft/s for velocity.

Table 2
Dimensional Characteristics of the BETRS Frequency Bands

Frequency Band	Approximate Mid-Band Frequency	Free-Space Wavelength λ at Mid-Band	Approximate Length of ½λ Dipole Antenna
150 MHz	155 MHz	1.94 m (6.35 ft)	0.93 m (3 ft)
450 MHz	457 MHz	0.66 m (2.15 ft)	0.32 m (1 ft)
800 MHz	841 MHz	0.36 m (1.17 ft)	0.17 m (6.7 in.)

Although propagation is essentially independent of the modulation used in narrowband systems, the way a link is analyzed (for example, the consideration of fade margin) differs between systems using analog and digital modulation. Most common are analog systems using frequency modulation (FM), but the characteristics of systems using common digital modulation methods, such as differential phase shift keying (DPSK) and quadrature amplitude modulation (QAM), also are discussed in this guide.

[7] The nomenclature “3E8” is shorthand for $3X10^8$; the E indicates exponent of 10.

4. The Propagation Problem

A typical propagation problem in point-to-multipoint systems consists of determining the required minimum power radiated from a transmitter to provide an acceptable quality of service over a pre-determined service area. A similar problem is determining the acceptable service area for a given radiated power (called "area prediction"). In point-to-point systems, the problem is to determine what is required to provide acceptable quality at a single subscriber location.

There are two main factors that have to be quantified to predict propagation. These are

- Median signal strength
- Signal variability.

The information required to determine these factors consists of:

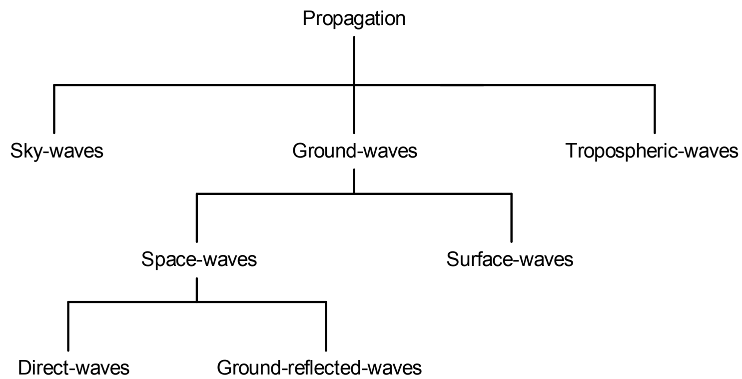
- Frequency
- Great Circle distance between the two radio terminal antennas
- Antenna height
- Polarization
- Terrain characteristics
- Electrical constants of the earth
- Atmospheric refractivity at the surface (radio climate)

Each item is discussed in the following sections.

Electromagnetic energy in the form of radio waves propagates outwards from a transmitting antenna. There are several ways in which these waves travel, much depending on the transmission frequency. The modes of propagation are shown in Fig. 1. In the VHF and UHF bands of interest, the frequencies usually are too high for ionospheric propagation. VHF and UHF frequencies can propagate as tropospheric waves. Tropospheric propagation is used in over-the-horizon transmission systems; however, high radiated powers and very sensitive receivers are required if this mode is to be used.

For the typical BETRS system, propagation takes place very close to earth's surface, and the radio waves are generically called ground-waves. Ground-waves can be conveniently subdivided into space waves and surface waves, and space waves can be subdivided into direct-waves and ground-reflected waves, as shown in Fig. 1. The direct-waves propagate via the direct path between the transmitter and receiver antennas. Ground-reflected waves reach the receiver antenna after one or more reflections from the ground.

Fig. 1
Radiowave Propagation Modes



The surface waves are guided along the earth's surface. Because the earth is not a perfect conductor, energy is extracted from the radio wave as it propagates to supply losses in the ground itself. The attenuation of this wave is directly affected by the ground conductivity and dielectric constant along the path. For any given frequency, the importance of each of the waves (surface, direct, ground-reflected) depends on the length of the propagation path.

The analysis of space-wave propagation in the frequency bands of interest takes into account the problems of reflections both from the ground and from natural and man-made objects. Diffraction over hill and mountain tops and buildings and refraction in the lower atmosphere also are important.

Propagation can be evaluated based on statistical models or deterministic models, or a combination of both. A statistical model considers terrain only in a general way and does not use specific terrain data while a deterministic model considers specific terrain data (such as the heights of intervening hills).

The results obtained from statistical models have limited usefulness in fixed radio systems design but, nevertheless, will be mentioned here because they can be helpful in quick analyses. Even though deterministic models specifically account for terrain effects, they still yield results with statistical uncertainty. A deterministic model gives a mean propagation loss and standard deviation according to some statistical function, typically a log-normal distribution.

A model usually will distinguish between three mutually independent propagation phenomena: Multipath fading; shadowing; and a large-scale path loss.

Multipath fading leads to fluctuations in the phase and amplitude of the signal. Depending on the source of the multipath signals, these fluctuations may be rapid or slow. Rapid fading can result from antenna movement on the order of a wavelength such as would be encountered in a mobile environment. Slow fading results from changing index of refraction in the atmosphere and multipath due to reflections from the ground, trees and surface water.

Shadowing is any statistical fluctuation of the received signal about some mean value due to terrain characteristics. Shadow losses depend on the degree of terrain roughness, which usually is quantified by the average difference between the valleys and hilltops along the path. Shadowing and multipath fading results in varying signal levels at the receiver, which follow a log-normal distribution about the mean. The mean value is determined by the large-scale path losses, which, in-turn, are determined by the path profile. The mean value gives the signal level with 50% probability.

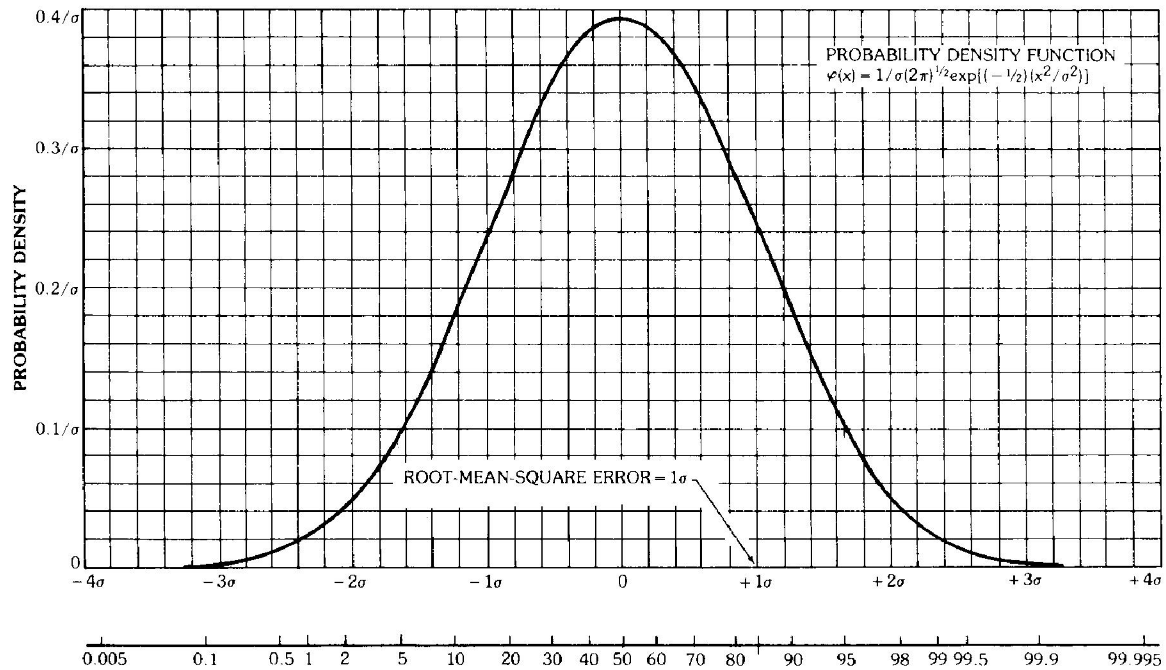
The large-scale path loss includes the three (mostly) predictable, loss mechanisms:

- Free-space loss
- Ground-wave loss
- Diffraction loss.

A frequently applied rule of thumb is to use an 8 dB standard deviation (σ) for all frequencies, although, as seen later, σ is somewhat frequency dependent. Using σ = 8 dB, the signal level found from any given measurement will fall within 8 dB (1σ) of the calculated mean value with a 68% probability and within 19 dB (2.33σ) with a 99% probability. This way of looking at probability considers both high and low signal levels (that is, the actual signal level will fall within +19 dB and -19 dB of the average 99% of the time). Higher than average signal levels are irrelevant in coverage or path analyses, so it is more meaningful to consider just the low end probabilities.

Given the standard deviation σ and the required probability, the fade margin can be derived from the normal distribution curve in Fig. 2. For example, if σ = 11 dB and the required probability is 90%, the required fade margin is approximately 1.3σ = 14 dB.

Fig. 2
Normal Distribution Curve
Source: [10]



A more accurate estimate of the standard deviation takes into account its dependence on frequency. Table 3 gives the standard deviation and expected additional path loss for 90% (1.3σ) and 99% (2.33σ) probability that the signal level is at least the value given (no lower value). These values would be added to the median path loss or used as a fade margin to achieve the desired path reliability.

Table 3
Path Loss Variability for BETRS Frequency Bands
Source: Fig. 4, [28]

Frequency	150 MHz	450 MHz	800 MHz
Std. Dev. σ	9 dB	11 dB	12 dB
50% ·	0 dB	0 dB	0 dB
90% ·	11 dB	14 dB	16 dB
99% ·	20 dB	25 dB	28 dB

· Loss added to median path loss to achieve probability given.

5. The Propagation Link Equation

The basic link equation for VHF and UHF propagation is given by

$$M = P_t - L_t + G_t - A_{PL} + G_r - L_r - P_{th} \quad (2)$$

where

M	=	Fade Margin (dB)
P_t	=	Transmitter power at the antenna connector on the radio (dBm)
L_t	=	Transmission line loss between the antenna connector on the radio and the connector on the transmitter antenna (dB)
G_t	=	Transmitter antenna gain with respect to an isotropic antenna (dBi) [Note: Gt(dBi) = Gt(dBd) + 2.15 dB]
A_{PL}	=	Total path loss between isotropic antennas (dB)
G_r	=	Receiver antenna gain with respect to an isotropic antenna (dBi)
L_r	=	Transmission line loss between the antenna connector on the radio and the connector on the receiver antenna (dB)
P_{th}	=	Receiver threshold sensitivity measured at the antenna connector on the radio (dBm).

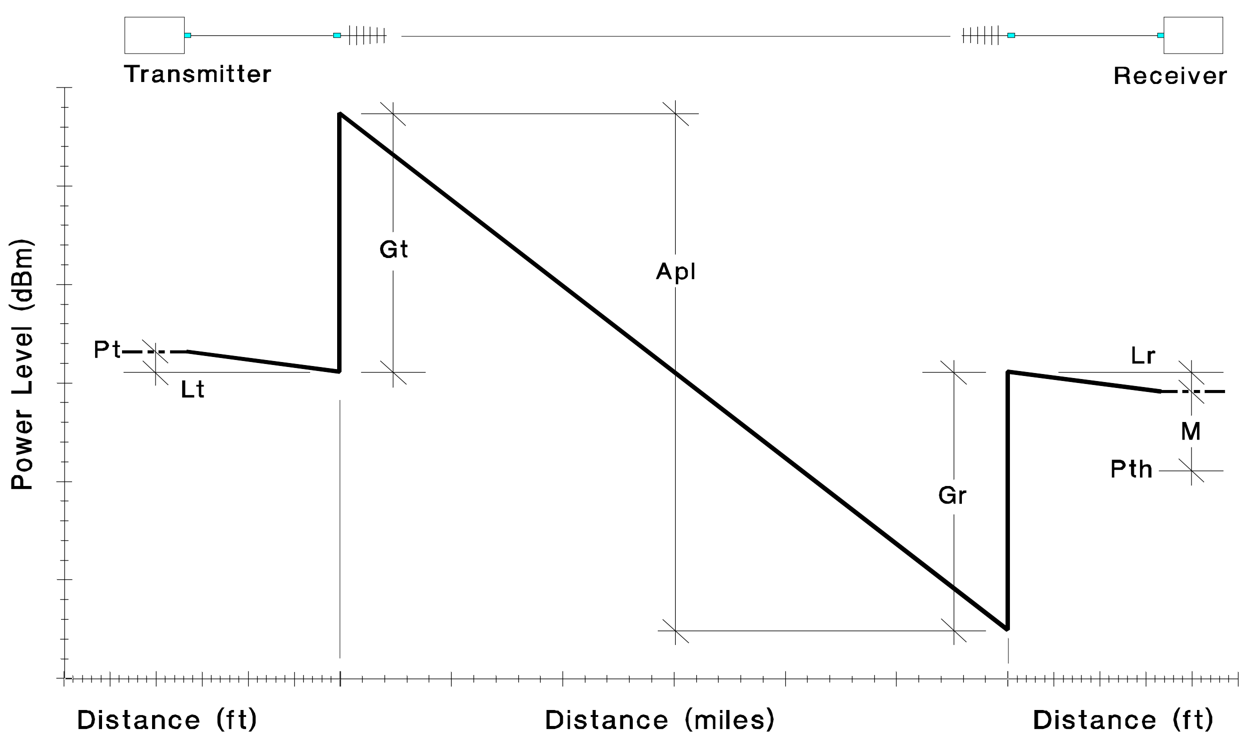
Equation (2) shows how each element of the link or associated parameter affects the fade margin. Fig. 3 shows a graphical representation of the equation. It is easy to rearrange the equation to solve for any parameter. For example, determining the required antenna gains for a given set of radio equipment with fixed transmitter power and receiver sensitivity and a path with predetermined loss and fade margin is easily solved from:

$$G_t + G_r = M - P_t + L_t + A_{PL} + L_r + P_{th}$$

Perhaps the most difficult parameter to deal with in a radio engineering problem is the path loss, so it is discussed at length in the following sections. Path loss is broken into several components of which the most fundamental is the free-space path loss. Any radio link, regardless of its spatial configuration, experiences path loss at least as great as the free-space loss.[8] Most terrestrial radio links also experience varying degrees of ground-wave loss, diffraction loss, foliage loss and, in urban areas, building loss. These loss components are added to the free-space loss to obtain the overall, or total, loss A_{PL} for the path.

[7] Under conditions where reflected waves are in-phase with the direct waves (additive reflection), the measured loss may be less than free-space loss, but this phenomenon is not used in link design.

Fig. 3
Propagation Equation in Graphical Form



6. Free-Space Loss

Free-space loss is the loss due to the inherent attenuation power law between a transmitter and receiver antenna free of any influence from surrounding terrain or objects. Such would be the case for two radio terminals in outer space. The free-space loss A_{fs} between two isotropic antennas is given by:[9]

$$A_{fs} = 20\log(\frac{4\pi d}{\lambda})\text{ dBi} = 10\log\left[\left(\frac{4\pi d}{\lambda}\right)^2\right]\text{dBi} \tag{3}$$

where d = distance between the transmitter and receiver antennas and λ = wavelength (both in compatible units). As can be seen from this expression, free-space loss increases with the square of the distance. This means at a given frequency, the loss increases by 6 dB for each doubling of distance. For example, the free-space loss at 457 MHz over a 7.5 mi path between two isotropic antennas is 107.3 dB. Over a distance of 15 mi, the loss is 113.3 dB.

Free-space loss can be rewritten in the following forms:

$$\begin{aligned} A_{fs} &= 36.6 + 20\log(d_{mi}) + 20\log(f_{MHz})\text{ dBi} \\ A_{fs} &= 32.4 + 20\log(d_{km}) + 20\log(f_{MHz})\text{ dBi} \end{aligned} \tag{4}$$

where d_{mi} = distance in mi, d_{km} = distance in km, and f_{MHz} = frequency in MHz.

The great circle distance may be determined using techniques given in Appendix F.

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[9] Losses in dB are given by positive numbers. Gain is a negative loss. The nomenclature dBi (decibels with respect to isotropic antennas) is used throughout this monograph to indicate that antenna gains are not included in the path loss calculation. In some discussions and examples, the i is dropped but still implied. An isotropic antenna radiates equally in all directions and, therefore, has a gain = 1 (0 dB). An isotropic antenna cannot be built but the concept of such an antenna is convenient in radiowave propagation work. Some propagation models are based on dipole antennas. Dipoles can be easily built and have a gain = 1.64 (2.15 dB) over an isotropic antenna. This is discussed further in the section on antennas later in this monograph.

7. Ground-Wave Loss

Ground-wave loss is due to the interaction of radio waves with the land they travel over. For line-of-sight conditions over a smooth surface (for example, a body of water) a *plane earth* is sometimes used in the analysis. Over a plane earth, the received signal consists of a direct line-of-sight wave, a wave reflected from earth's surface, and a surface wave. The phasor sum of the direct wave and the ground-reflected wave is called the space-wave.

For most VHF and UHF communications, the surface wave is small compared to the direct- and reflected-waves. However, the surface wave may be significant under certain conditions. The phase difference Δ resulting from the difference in the path length of the direct- and reflected-waves is given by

$$\Delta \approx \frac{4\pi h_t h_r}{\lambda d} \text{ radians} \tag{5}$$

where d = distance between the transmitter and receiver antennas >> $5(h_t + h_r)$, h_t = height of the transmitting antenna above ground level, and h_r = height of the receiving antenna above ground level (the ground or water level is assumed to be constant). All parameters must be in compatible units (for example, all m or all ft).

Where Δ > 0.5 radians, the loss A_R over and above the free-space loss (*excess loss*) due to the surface-wave is given by

$$A_R \approx 20\log\left[\frac{1}{2\sin(\frac{2\pi h_t h_r}{\lambda d})}\right] \text{dBi} \; (\Delta > 0.5 \text{ radians}). \tag{6}$$

Equation (6) assumes h_t and h_r exceed the minimum effective height discussed in later paragraphs of this section. Ignoring for the moment the reflected wave, the total ground-wave loss A_{GR} over a plane earth is

$$A_{GR} = A_{fs} + A_R \approx 20\log\left[\frac{2\pi d}{\lambda \sin(\frac{2\pi h_t h_r}{\lambda d})}\right] \text{dBi} \; (\Delta > 0.5 \text{ radians}) \tag{7}$$

For this case, the principal effect of the ground is to produce interference fringes or lobes so the field intensity at a given distance and frequency oscillates around the free-space field as either antenna height is increased. This expression applies only to very short paths (< 2 mi at typical BETRS frequencies and antenna heights). The loss, in dB, can reach very high values whenever the sine function equals or is close to zero indicating high levels of subtractive interference. Under certain conditions, it is possible this expression will give a loss that is less than the free-space value alone. If this happens, the free-space value should be used.

Where Δ becomes very small (< 0.5 radians), the value of the sine function approaches the value of its argument. In this situation, the component of loss A_S over and above free-space loss between two isotropic antennas due to the surface wave is given by

$$A_S \approx 20\log\left(\frac{\lambda d}{4\pi h_t' h_r'}\right) \text{dBi } (\Delta < 0.5 \text{ radians}) \qquad (8)$$

where λ = wavelength in units compatible with the other parameters and h_t' and h_r' are the actual antenna heights above ground or the minimum effective heights, whichever are larger. The minimum effective height takes into account that the received field strength close to the ground is practically independent of the height. The actual value for minimum effective height depends on the ground conductivity and the wave polarization.[10] The graph in Fig. 4 shows the minimum effective height for various earth conductivities. Sea water has the highest conductivity; frozen ground has low conductivity and would be classified as "poor soil" in the graph.

For systems operating at 450 and 800 MHz, the minimum effective height is very small, which means the actual physical height should be used in all practical cases. For 150 MHz systems, the minimum effective height over sea water is 20 ft but much less over land. Over sea water 20 ft should be used if the antenna actual physical height is less than 20 ft (say, on a boat); otherwise, use the actual height. It is important to remember that too low of actual antenna height will affect antenna impedance and radiation pattern regardless of minimum effective height.

The total ground-wave loss A_{GS}, taking into account the surface-wave but ignoring the reflected wave, is given by

$$A_{GS} = A_{fs} + A_S = 20\log\left(\frac{d^2}{h_t' h_r'}\right) = 10\log\left[\frac{d^4}{(h_t' h_r')^2}\right] \text{dBi} \qquad (9)$$

As can be seen from equation (9), the path loss increases proportionately with the 4th power of the distance. Also, note the total ground-wave loss is independent of operating frequency. This is contrary to intuition and experience and indicates a limitation in equation (9).

If both antenna heights are less than approximately 150 ft for 150 MHz, 80 ft for 450 MHz and 50 ft for 800 MHz, the earth's curvature increases the loss calculated from A_{GS} as given above. This additional loss depends on both frequency and distance between the transmitter and receiver antennas. For paths between 10 and 40 mi, the additional loss A_C can be approximated from

$$\begin{aligned} A_C &\approx 0.4d - 3.5 \text{ dB for 150 MHz band} \\ A_C &\approx 0.6d - 4.0 \text{ dB for 450 Mhz band} \\ A_C &\approx 0.8d - 6.0 \text{ dB for 800 MHz band} \end{aligned} \qquad (10)$$

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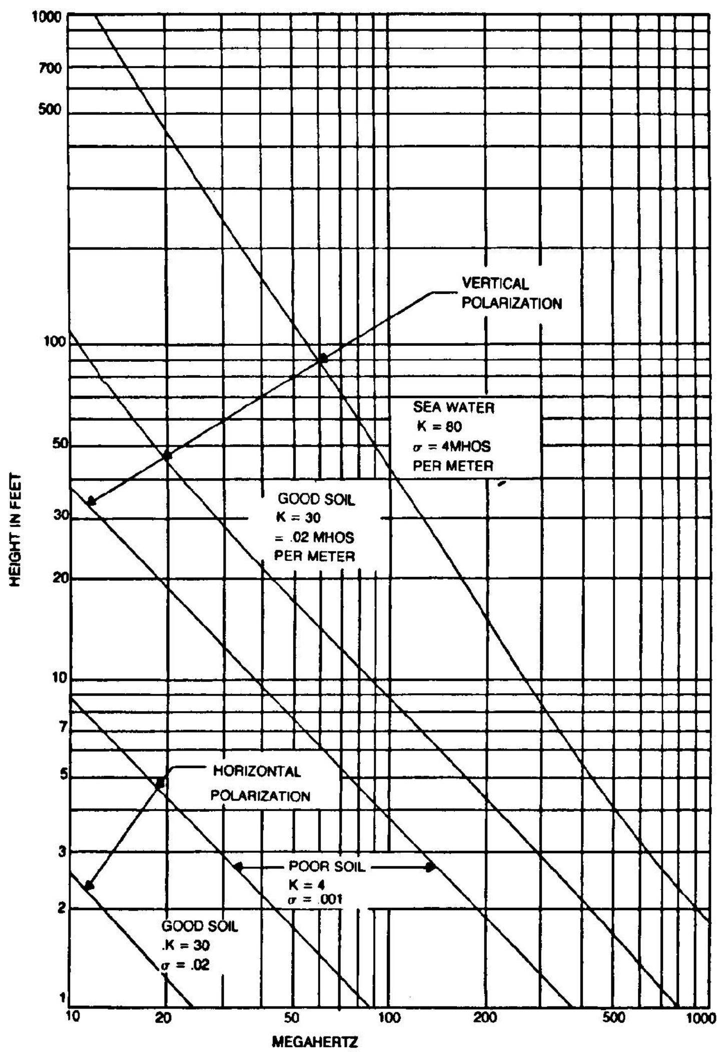
[10] Vertical polarization normally is used with BETRS systems.

where d = total path distance in mi. The total path loss includes the additional loss calculated above, or

$$A_{TC} = A_{GS} + A_C = A_{fs} + A_S + A_C \text{ dBi} \tag{11}$$

On the paths used in the previous example, assume the transmitter and receiver antenna heights are 50 ft and 20 ft, respectively. The excess loss over the 7.5 mi path is 16.6 dB and over the 15 mi path is 22.7 dB. The total path loss (including free-space path loss) for each path at 457 MHz is 123.9 and 135.9 dB, respectively. Note that Δ = 0.02 radians in this example.

Fig. 4
Minimum Effective Antenna Heights
Source: Fig. 3, [23]

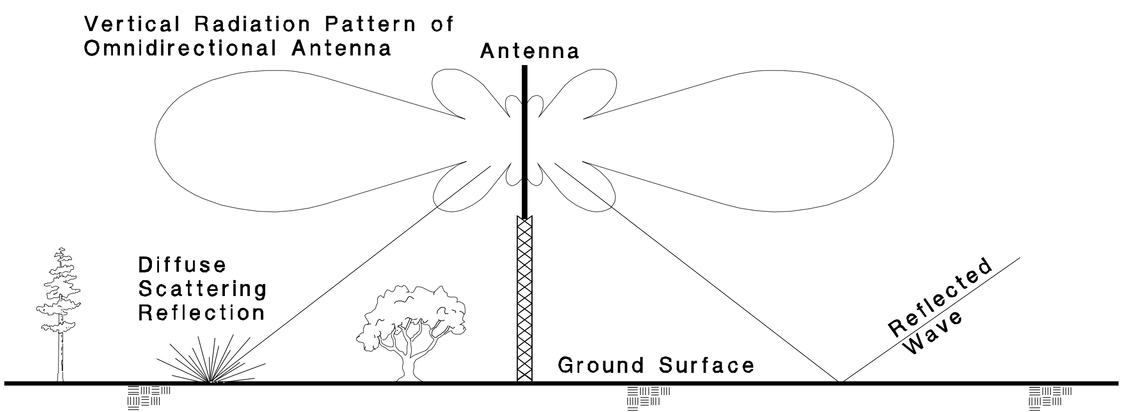


In low angle propagation through the atmosphere, the effects of the ground are significant for reasons in addition to those previously discussed. Antenna beams always radiate substantial amounts of transmitted power toward the ground as can be seen in Fig. 5.

In some cases - for example heavily forested or hilly and vegetated terrain - the ground may act as a diffuse scatterer (shown on the left side of Fig. 5) and cause relatively benign effects on fixed radio links. Foliage effects are discussed in a later section. In other cases, the ground will act as a good reflector in small and isolated areas or over large areas like bodies of water, flat planes or desert areas (shown on the right side of Fig. 5).

The reflection coefficient of flat areas on the ground or water surfaces always is very high regardless of the specific soil types and polarization because the grazing angle of the radio wave typically is very small. Strong reflections can cause significant signal level degradation or enhancement at receivers depending on the phase of the reflected waves with respect to the direct waves and other reflected waves. The magnitude and phase of the reflected wave is difficult to determine accurately. It may depend on the season and exact position and height of the antenna. Even though reflected waves may be significant on a path, they are ignored in most path analyses. Digital radio systems may not work reliably in areas where reflected waves exist.

Fig. 5
Types of Ground Reflections



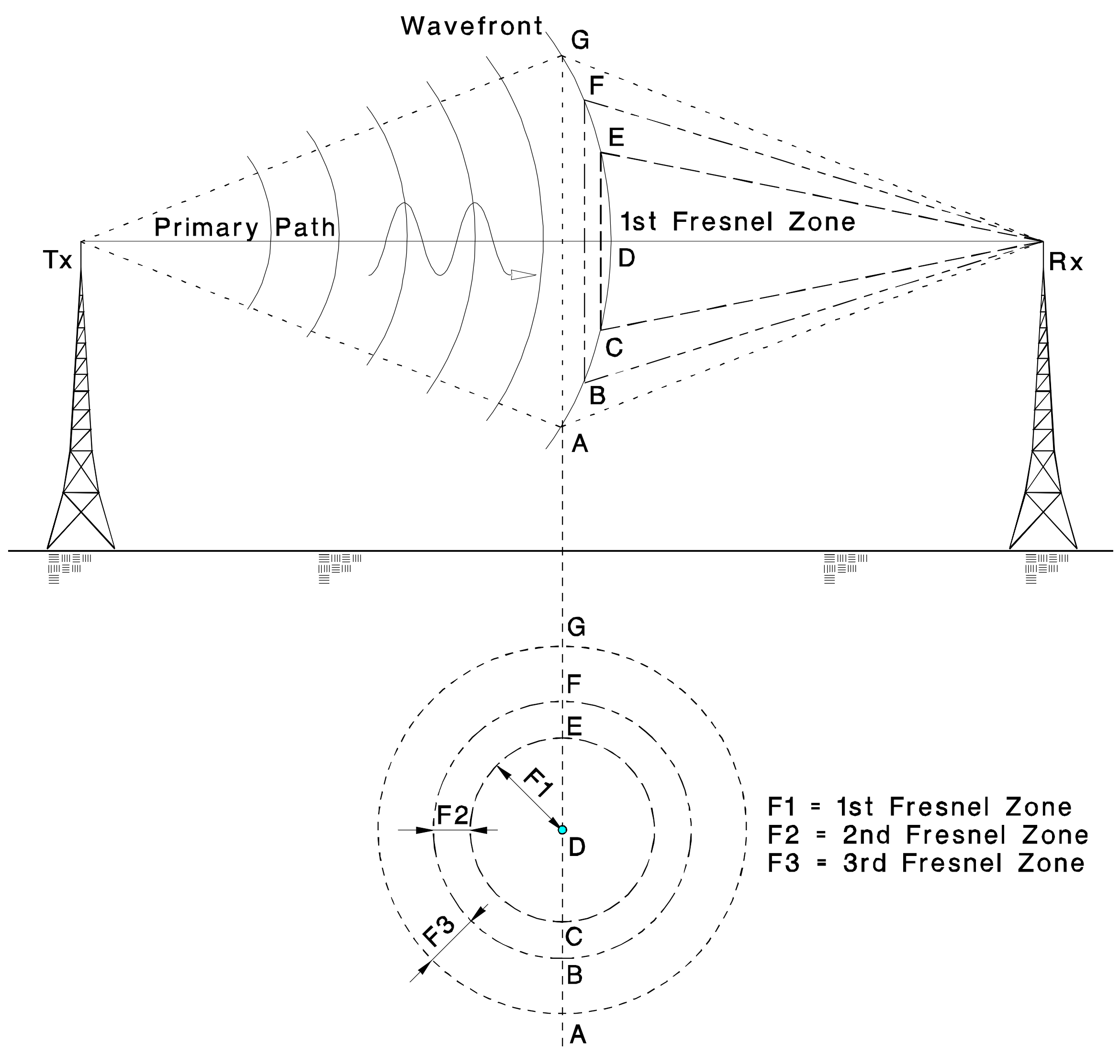
Propagation over lakes and shallow coastal waters is the same as propagation over a smooth, but highly conductive, earth. Propagation over rough seas is similar to rough earth. It is important to remember that, even on line-of-sight paths, diffraction losses can be expected if there is inadequate Fresnel zone clearance as mentioned in the next section.

If the path is from land to a small fishing boat, the boat antenna could be quite low. The radio wave received by and transmitted from this antenna will be primarily ground-wave and the antenna physical height may be different than its electrical, or effective, height. The effective height, if greater than the physical height, should be used in propagation analyses.

8. Fresnel Zones and Diffraction Loss

Fixed point-to-point radio engineering rules frequently require a path to have a certain clearance from the terrain. This clearance is measured in terms of Fresnel zones. To visualize what a Fresnel zone is, consider a transmitter and receiver sufficiently high above the ground as shown in Fig. 6. The primary wave travels in a straight line between T_x and R_x. Secondary waves travel in symmetrical, but longer, paths about this straight line.

Fig. 6
Fresnel Zone Geometry



On a perpendicular plane at some point along the transmission path, concentric circles can be drawn that represent the loci of these secondary waves traveling from T_x to R_x.. The radius of any given circle on this plane depends on its distance from the transmitter and receiver antennas. The radii of the circles are such that the total path lengths of the secondary waves are $n\lambda/2$ greater than the primary path, where n is an integer. Thus, the distance $T_xC + CR_x$ is $\lambda/2$ longer than the primary path, $T_xB + BR_x$ is λ longer than the primary path, and so on. The contribution of each successive zone to the field at the receiver thus alternates out-of-phase and in-phase with the primary-wave. The zones are called Fresnel zones, and the radius of the *n*th Fresnel zone at any point is given by:

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \tag{12}$$

where d_1 = the distance from the transmitter to the point in question and d_2 = distance from the receiver to the point in question ($d = d_1 + d_2$). The first Fresnel zone is the region of space that contains all paths with lengths exceeding the direct path by less than one-half a wavelength, $\lambda/2$.

If an obstructing screen with a central hole replaces one of the perpendicular planes, and the central hole size is increased, successive secondary waves are allowed to pass in addition to the primary wave. For n = 1 and a reflection coefficient of -1 (across the knife-edge screen), the secondary wave arrives in-phase and reinforces the field at R_x. For n = 2, the wave arrives out-of-phase and reduces the field at R_x. It can be seen that the field at R_x oscillates about the free-space value that would exist in the absence of the screen. The amplitude of the oscillation decreases rapidly as the radius is increased, so only the first few zones are important.

In real systems, the signal level at the receiver is influenced by hills and mountains that lie in, or close to, the line-of-sight path as shown in Fig. 7. The right-hand side of this illustration gives an indication of how the diffraction loss varies with obstruction height. About half of the energy reaching the receiving antenna passes through the first Fresnel zone. For the knife-edge case, if the obstacle does not encroach into the first few Fresnel zones, the field at R_x is unaffected. However, as the obstacle height is increased, the field oscillates with increasing amplitude in the manner described above. Where the obstruction does not have a knife-edge, this oscillation is not apparent.

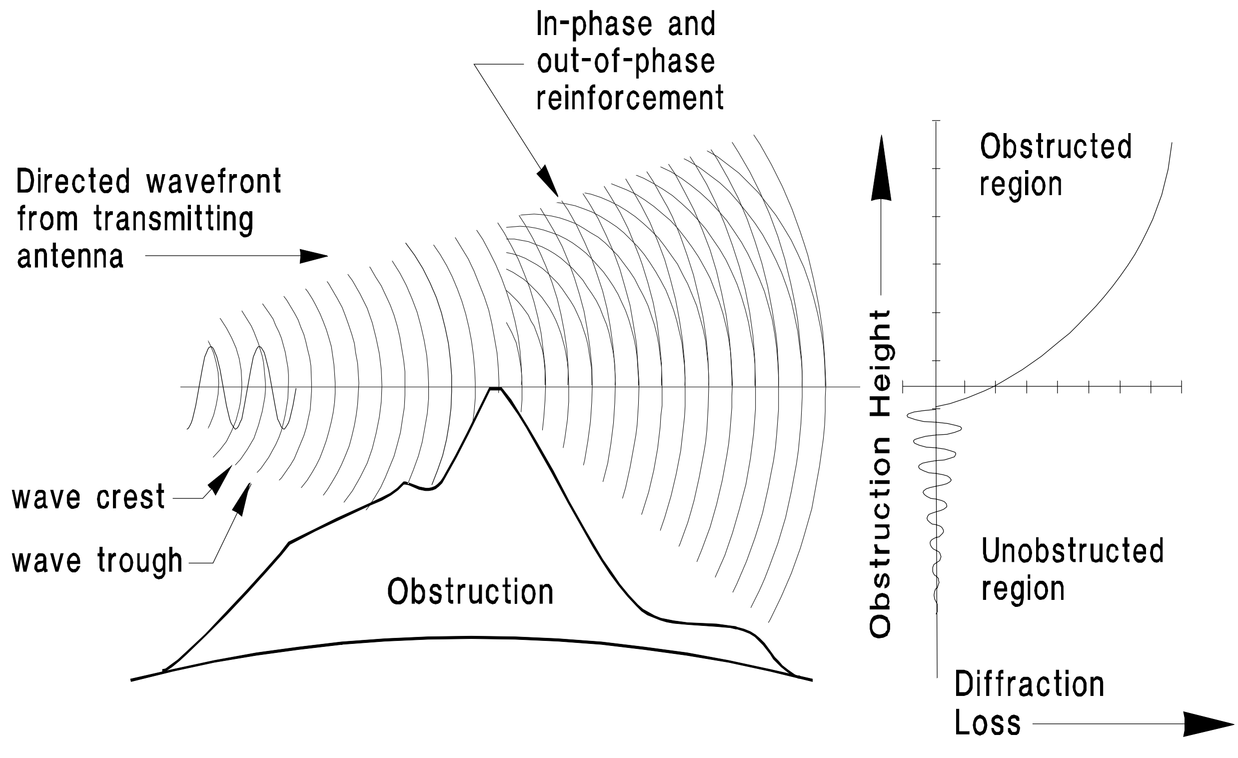
At the point where the obstacle's edge is just in line with the direct path between T_x and R_x (grazing), the field at R_x is 6 dB below the free-space value. As the obstacle's height is increased farther and it blocks the line-of-sight path, the oscillation ceases and the field decreases steadily with further height increase. The rate of field decrease depends on the characteristics of the obstacle's edge. The excess path loss (that is, loss over and above the free-space loss) due to diffraction is shown in Fig. 8 as a function of the Fresnel diffraction parameter, *v*. *v* is a function of obstacle clearance h (with respect to the center of the radio path), wavelength λ, distance from the transmitter d_1, and distance from the receiver d_2 and is given by

$$v = -h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} = -h\frac{\sqrt{2}}{F_1} \tag{13}$$

The obstacle clearance h is negative where the obstacle is below line -of -sight (unobstructed conditions) and positive for obstructed conditions.[11] The sign of the diffraction parameter *v* is opposite of h. This definition of *v* implies the obstacle obstructs $v/\sqrt{2}$ Fresnel zones of the radio wave.

[11] Report 715-3 of the CCIR uses the reverse; that is, h is negative for obstructed conditions.[57]

Fig. 7
Radiowave Diffraction



Even though the diffraction loss is derived from ideal knife-edge conditions, it still has practical applications because many obstacles approximate a knife-edge. A frequently cited requirement for fixed, light-route, point-to-point microwave paths is a clearance of the line-of-sight path ≥ 0.6 first Fresnel zone radius from any obstacles along the path. The source of this requirement can be seen in Fig. 8. For the unobstructed case with 0.6 F1 clearance, h = –0.6 F1 or v = +0.85. This equates to a diffraction loss of 0 dB.

Smaller clearances yield higher losses. The 0.6 F_1 requirement is valid in BETRS applications. If the path is line-of-sight but without any clearance (grazing), a 6 dB (or more) additional path loss over the free-space value can be expected.

In general, the total path loss A_D when diffraction is present is given by

$$A_D = A_{fs} + A_d \text{ dBi} \tag{14}$$

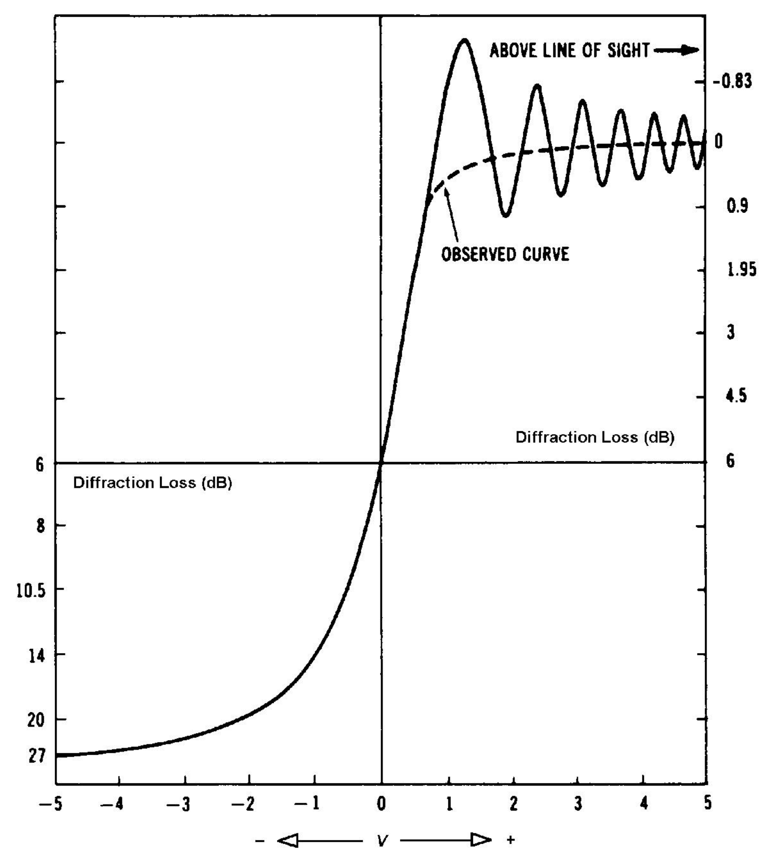
where A_d = diffraction loss over and above free-space loss. A_d for positive values of v (negative values of h) can be approximated by:[13]

$$A_d = \begin{cases} 0 \text{ dB for } v \ge 1 \\ 20\log\left(\dfrac{1}{0.5+0.62v}\right) \text{dB for } 0 \le v \le 1 \end{cases} \tag{15}$$

and for negative values of v (positive values of h) by:

$$A_d = \begin{cases} 20\log\left(2e^{-0.95v}\right) \text{dB for } -1 \le v \le 0 \\ 20\log\left(\dfrac{1}{0.4-\sqrt{0.1184-(0.1v+0.38)^2}}\right) \text{dB for } -2.4 \le v \le -1 \\ 20\log\left(-\dfrac{v}{0.225}\right) \text{dB for } v \le -2.4 \end{cases} \tag{16}$$

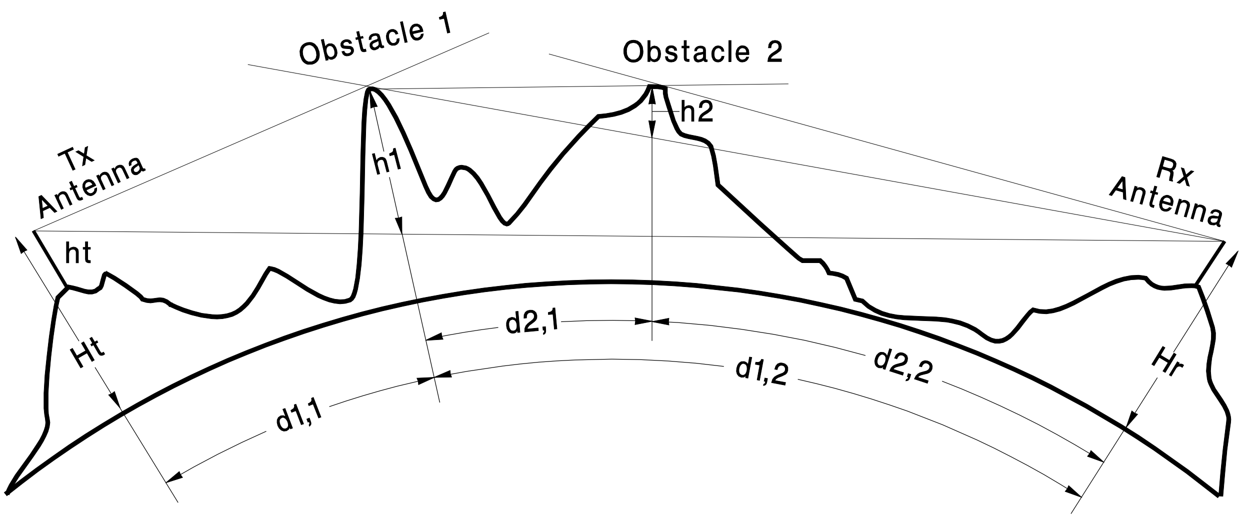
Fig. 8
Excess Path Loss Due To Knife-Edge Diffraction
Source: Fig. 2.20, [12]



The knife-edge assumption for diffraction loss has obvious limitations because real obstructions do not always have knife edges, paths frequently have more than one obstruction, and there usually are other path characteristics that affect the overall loss.

A frequent refinement is to approximate the path profile by multiple knife-edges. The obstruction height for the first obstruction is taken at its true value above the direct path between the transmitter and receiver antennas as if none of the other obstructions are present. The second obstruction height is found by taking the height above the direct path between the top of the first obstruction and the receiver, and so on, as illustrated in Fig. 9. In this illustration, the height of obstacle 1 is h1 and the height of obstacle 2 is h2. The respective distances of obstacle 1 from the transmitter and receiver are d1,1 and d1,2. A virtual transmitter is placed on the top of obstacle 2 for the next calculation giving distances d2,1 and d2,2 of obstacle 2 from the virtual transmitter on obstacle 1 and actual receiver. There are variations of this method. The actual loss across multiple obstructions is problematic and cannot be determined very accurately. Such paths should be avoided in the design stage because the path probably will not work.

Fig. 9
Height of Multiple Obstructions



There are two important factors that cause the diffraction loss calculated for negative values of v in equation (16) to be understated. First, obstructions most often have rounded edges rather than knife-edges and this increases the path loss. One way of refining the knife-edge assumption is to replace the knife-edge with a cylinder of radius *r*. In this case, an additional loss is introduced that must be added to the excess diffraction loss given in equation (16). The additional loss is given by:[17]

$$A_{rd} = 11.7\alpha\sqrt{\frac{\pi(r)}{\lambda}} \text{ dB} \tag{17}$$

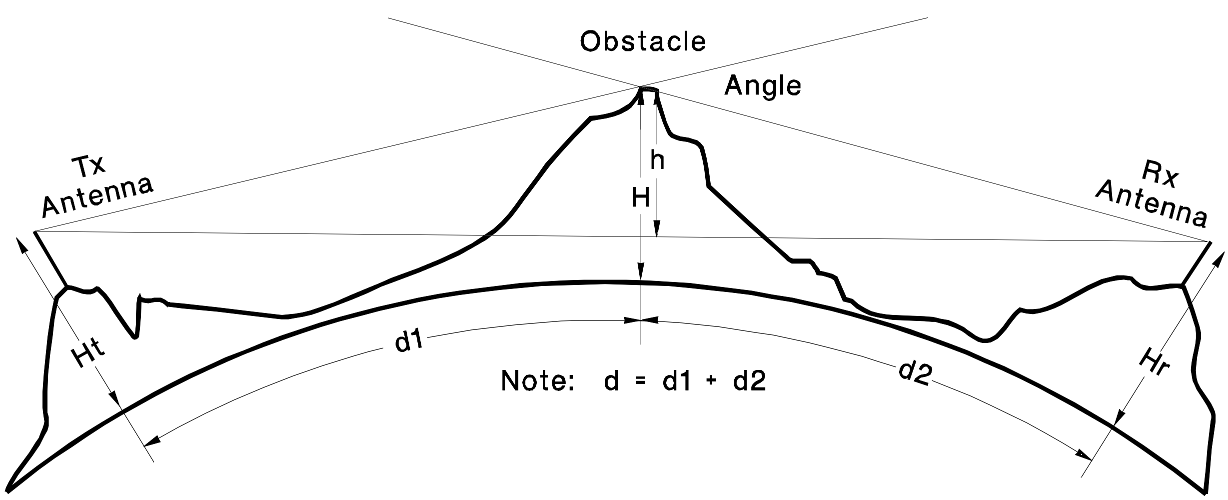
where α is the angle between the radio waves tangent to the obstacle as shown in Fig. 10. This angle can be found from:

$$\text{Angle } \alpha = \frac{H - H_t}{d_1} + \frac{H - H_r}{d_2} + \frac{d_1 + d_2}{Ka} \text{ radians} \quad (18)$$

where H = obstacle height AMSL, H_t = transmitter antenna height AMSL, H_r = receiver antenna height AMSL, K = earth radius factor (typically 4/3), and a = earth's true radius (6,370 km or 20.9E6 ft). The other parameters have been previously defined. All distances and heights must be in compatible units. The total excess loss over a rounded obstacle is

$$A'_d = A_d + A_{rd} \text{ dBi} \quad (19)$$

Fig. 10
Angle Between Radio Waves Tangent To An Obstacle



If the hilltop is rough due to the presence of trees or large rocks, the diffraction loss (in dB) is about 65% of that found in equation (17). The case where $r = 0$ is equivalent to a knife-edge, and the resulting curve-edge adjustment is zero. The actual value of r to use in practical work is somewhat subjective. It is possible to estimate an equivalent radius when an obstruction is drawn on a profile with the *same* horizontal and vertical scaling. This is illustrated in Fig. 11, where the equivalent radius r is given in terms of elevation e and distance c (all in compatible units) by:

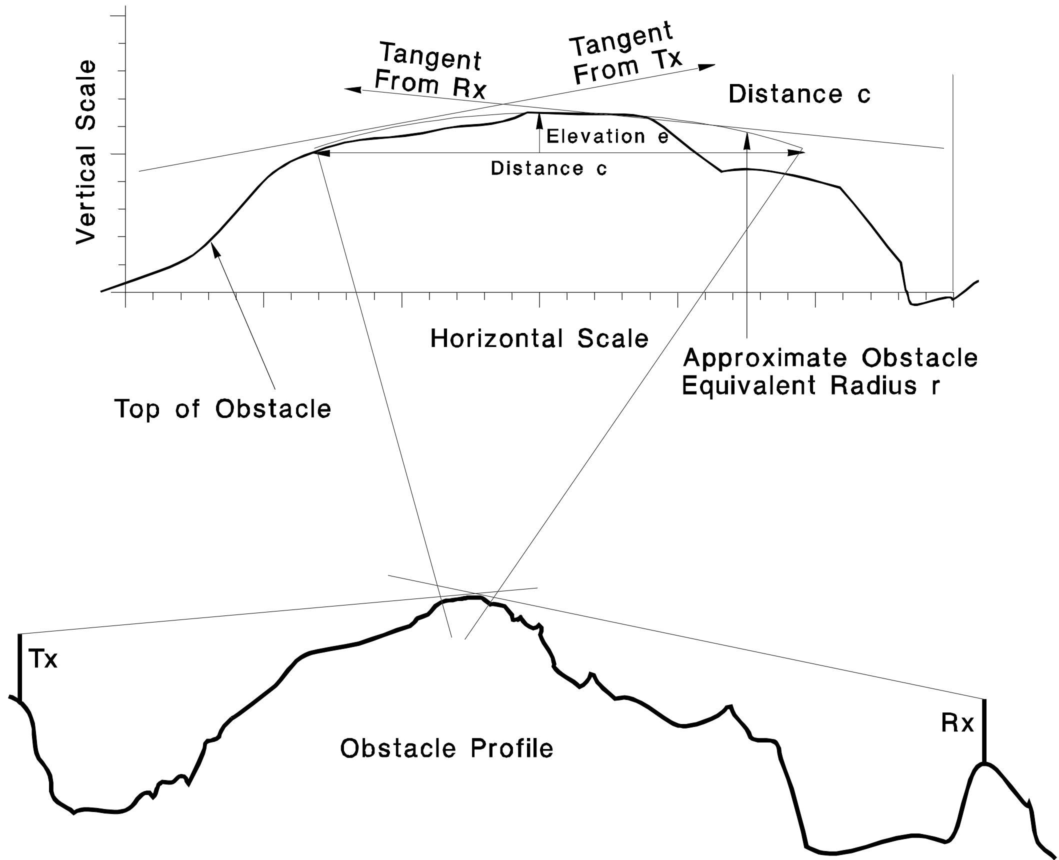
$$r = \frac{\left(4e^2 + c^2\right)}{8e} \quad (20)$$

As an example of the necessary calculations, consider a point-to-point path with the following parameters:

H = 1,375 ft AMSL, H_t = 930 ft AMSL, H_r = 175 ft AMSL
d_1 = 7.5 mi, d_2 = 8.5 mi
c = 500 ft, e = 50 ft
f = 457 MHz
K = 4/3

Equation (20) gives the equivalent radius r as 650 ft and equation (18) gives the angel α as 0.041 radians. The wavelength λ is given by equation (1) as 2.15 ft. The excess loss A_{rd} from equation (17) is then 14.8 dB. This value is added to the diffraction loss for a knife edge obstacle found from equation (15).

Fig. 11
Estimating the Equivalent Radius of an Obstruction



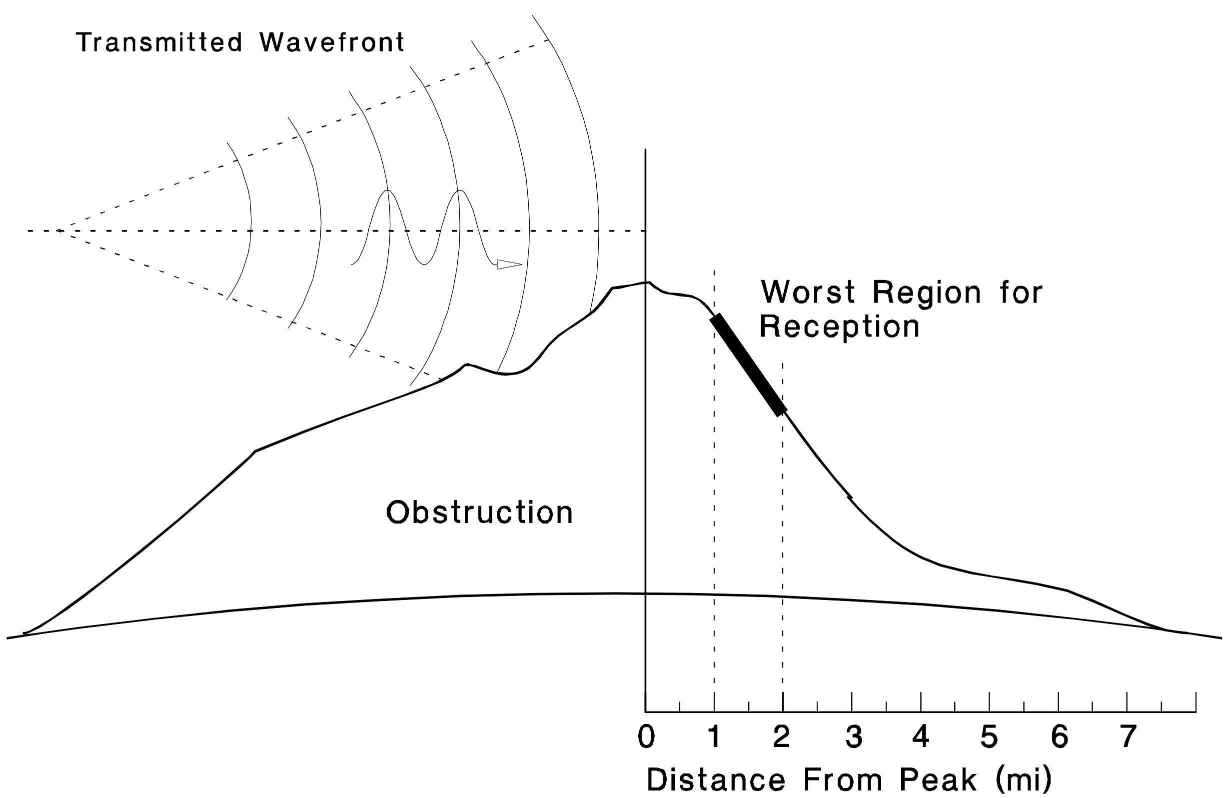
The second factor that causes the knife-edge diffraction loss to be understated occurs close to the backside of obstructions. Okumura found experimentally that the loss is extraordinarily high within the first few miles in the shadow zone, becoming maximum for receiver distance d_2 from the obstacle of 1 to 2 mi and less at smaller and greater distances.[33] See Fig. 12. The amount of additional backside loss A_{bd} depends on the transmitter distance d_1 from the obstacle as follows:

- For $d_1 < 9$ mi, A_{bd} is about 18 dB
- For d_1 around 19 mi, A_{bd} is around 14 dB
- For $d_1 > 37$ mi, A_{bd} is around 7 dB.

The total excess diffraction loss A_d'', taking into account the additional backside loss, is given by:

$$A_d'' = A_d + A_{bd} \tag{21}$$

Fig. 12
High Loss Region on Backside of Obstructions



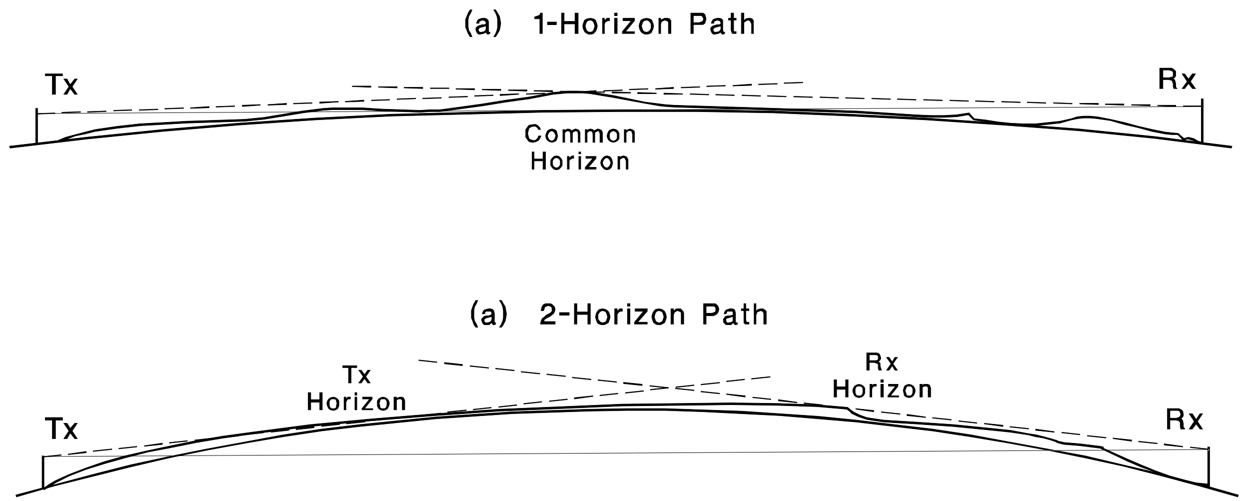
To round out the discussion of diffraction loss, consider over-the-horizon paths. These are diffraction paths in which a relatively smooth earth is the obstacle. In the previous discussions, mountains or hilltops obstructed the path. Now, a smooth earth (say a large lake, the ocean, or relatively flat land) obstructs the path.

There are two situations that may exist, a 1-horizon path as shown in Fig. 13(a) and a 2-horizon path as shown in Fig. 13(b).

The diffraction loss from a 1-horizon path is the same as Fig. 8, and the associated expressions for A_d. The 2-horizon paths provide at least 30 dB of loss at v = –1, giving poor propagation as would be expected. Under some conditions, communication may still be possible using tropospheric waves rather than diffraction mechanisms. However, the scatter losses in the troposphere are very high and reliable BETRS links cannot be designed using tropospheric waves.

It is clear from the foregoing discussions that predicted diffraction losses can greatly exceed the loss found from the assumption of a simple knife-edge obstruction. This should be no surprise because experience shows diffraction paths do not work at all or work poorly more often than not. It is for this reason a diffraction path should never be designed and implemented without a path survey using live equipment. The path survey should be made at varying times of the year and under varying conditions, if possible.

Fig. 13
Over-the-Horizon Paths



9. Foliage and Buildings

In the summer, deciduous trees (trees that shed their leaves in the fall and grow new ones in the spring) cause additional signal loss at frequencies above 100 MHz, especially for vertical polarization. Several foliage loss models have been proposed, which are discussed below.

When an antenna is surrounded by moderately thick trees and is below tree-top level, the average additional loss at VHF may be 2 to 3 dB.[24] The tree losses increase with frequency. The difference in path loss through trees with and without leaves is 3 to 5 dB. From a design point-of-view, if there is a heavy forest in the area, then a 10 dB to 14 dB allowance should be made, in addition to the value from the propagation path loss model used, to compensate for the summer foliage loss. If the area is covered by evergreens, this allowance would apply year-around.

As an alternate to using the fixed loss values, the following approximate expressions can be used for subjective estimates of foliage level around the receiver antenna site:[55] These expressions assume the antennas are below the level of the foliage.

$$\begin{aligned} &\text{Dense Foliage Loss} = 65.0\{0.244[\log(f) - 0.442]\}\ \text{dB} \\ &\text{Sparse Foliage Loss} = \text{Dense Foliage Loss} - 6\ \text{dB (for Dense Foliage Loss} > 6\ \text{dB)} \end{aligned} \tag{22}$$

where f = frequency in MHz. Another set of expressions for excess loss through foliage (in this case, dense, dry, in-leaf trees) is:[17]

$$\text{Foliage Loss} = \begin{cases} 0.19 f^{0.284} d_f^{\ 0.588}\ \text{dB for } 14 < d_f < 400 \\ 0.063 f^{0.284} d_f\ \text{dB for } 0 \le d_f \le 14 \end{cases} \tag{23}$$

where d_f = average path length through the trees in m.

The foliage loss from these expressions should be added to the path loss from the propagation path loss model. Where the antennas are below tree level, the extra loss caused by the forest vegetation can be quite high. The forest is sometimes modeled as a lossy dielectric slab at frequencies between 30 and 1,000 MHz.

The losses given in Table 4 are used where both the transmitter and receiver antennas are immersed in forest vegetation.[58] These losses are very high and it is easy to conclude that antennas never should be deliberately placed in the trees. It is typical to require a cleared area around the antenna with a cleared radius equal to 15 times the structure height.

Table 4
Forest Vegetation Loss (vertical polarization)

Frequency Band	Excess Loss
150 MHz	0.06 dB/m
450 MHz	0.12 dB/m
800 MHz	0.18 dB/m

A CCIR (now ITU-R) model, which was empirically developed in Sweden and also applied successfully in Germany, characterizes the forest between the transmitter and receiver by two parameters, vegetation density ρ (%) and percentage of forest along the transmission path η(%).[58] The vegetation loss as a function of frequency and distance is given by:

$$v = v_0(\eta\%)(\rho\%)\ \text{dB} \qquad (24)$$

where

$$v_0 = 46 - 15.5\log(f_{MHz}) + 45\log(d_{km})\log(f_{MHz} - 2) \qquad (25)$$

and f_{MHz} = frequency in MHz and d_{km} = distance in km. This model is based on η% = 100% and ρ% = 75%. η% is a measure of the trees per square unit and their average diameters and will be somewhat subjective because the CCIR report gives no guidance.

For distances of the transmitter and receiver antennas greater than about five times the tree height, the foliage loss can be assumed to be caused by knife-edge diffraction loss, and the loss calculations can be performed as described for diffraction conditions.

Trees near the receiver antenna may set up standing waves, which will affect the receive level. Thus, movement of the antenna a few ft in this environment may have a large effect.

Buildings in the vicinity of the receiver antenna site contribute to multipath losses. Approximate expressions for loss due to buildings are:[55]

$$\begin{aligned}&\text{City Bldg Loss} = 16.5 + 15\log(f/100) - 0.12d\ \text{dB}\\&\text{Residential Bldg Loss} = \text{City Bldg Loss} - 12\ \text{dB (for City Bldg Loss} > 12\ \text{dB)}\end{aligned} \qquad (26)$$

where d = distance in km. The building loss, as with foliage loss, should be added to the path loss from the propagation path loss model.

10. Other Path Models

In general, for typical path profiles encountered in rural areas, the total large-scale loss A_{path} is caused by a combination of free-space, ground-wave, and diffraction loss. Several expressions for combining the expressions have been proposed. These include simple addition, as previously mentioned, or slightly more complicated methods, including:

$$A_{path} = A_{fs} + \sqrt{A_s^{\ 2} + A_d^{\ 2}} \text{ dBi} \qquad (27)$$

and

$$A_{path} = A_{fs} + A_r + A_d \text{ dBi} \qquad (28)$$

where A_s = empirically modified version of As previously given, and A_d' (eq. 19) or A_d'' (eq. 21) may be substituted for A_d (eq. 15 and 16) depending on the diffraction loss mechanisms being modeled. Note that using both overstates the diffraction loss. An empirical statistical model frequently used is:[28]

$$A_{path} = 10\log d^4 - 10\log(h_t h_r)^2 + 10\log(f_c / 40 \text{ MHz})^2 \text{ dBi} \qquad (29)$$

or

$$A_{path} = 40\log d - 20\log(h_t h_r) + 20\log(f_c / 40 \text{ MHz}) \text{ dBi} \qquad (30)$$

where f_c = frequency in MHz. This model is seen to be identical to A_{GS} given in eq. (9) with the addition of an empirically determined frequency dependent term. This model is a general form of

$$A_{path} = 10\log d^{\beta} + A_0 \text{ dBi} \qquad (31)$$

where β = empirically determined propagation exponent and A_0 = empirical constant which depends to some degree on the frequency and antenna heights. β will vary from approximately 2 to 4. For the free-space limiting case, $\beta = 2$, and for the ground-wave limiting case, $\beta = 4$. For practical path profiles, which fall in between free-space and ground-wave, β = 2.6 to 3.2.

The so-called Okumura models are highly accurate graphical propagation models based on measured diffraction losses in urban areas. These models, which originally were given in graphical form, apply to paths up to 100 km over built-up areas.

Hata reduced Okumura's graphical information to a series of equations that lend themselves to mechanized analysis. Because Okumura's studies were made in a mobile environment, Hata's equations have limited application in fixed BETRS systems. This is especially true because Hata's equations apply to path lengths between 1 and 20 km (0.6 and 12 mi). Nevertheless, the equations are given here so the reader can judge their suitability to a particular path. It should be noted the "open area" below (and used by both Okumura and Hata) is really large areas of plowed ground or large built-up areas with low buildings, something not found in rural Alaska. The Hata equations are meant to be used without further correction for foliage and buildings.[29]

Urban Area Path Loss:

$$A_{pu} = 69.55 + 26.16\log f - 13.82\log h_t - a(h_r) + (44.9 - 6.55\log h_t)\log d \text{ dB} \qquad (32)$$

where A_{pu} = path loss, f = frequency in MHz, h_t = transmitter antenna height 30 to 200 m, d = distance 1 to 20 km, and $a(h_r)$ = correction factor for the receiver antenna height given as follows:

Medium - Small City:

$$a(h_r) = (1.11\log f - 0.7)h_r - (1.56\log f - 0.8)\text{ dB} \qquad (33)$$

Large City:

$$\begin{aligned} a(h_r) &= 8.29[\log(1.54h_r)]^2 - 1.1\text{ dB (for f} \le 200\text{ MHz)} \\ a(h_r) &= 3.2[\log(11.75h_r)]^2 - 4.97\text{ dB (for f} \ge 400\text{ Mhz)} \end{aligned} \qquad (34)$$

where h_r = receiver antenna height 1 to 10 m.

Suburban Area Path Loss:

$$A_{ps} = A_{pu} - 2[\log(f/28)]^2 - 5.4\text{ dB} \qquad (35)$$

Open Area Path Loss:

$$A_{po} = A_{pu} - 4.78[\log f]^2 + 18.33\log f - 40.94\text{ dB} \qquad (36)$$

These equations assume the transmitter antenna height is the height of the radiation center above average terrain between 3 and 15 km toward the receiver. Eq. (32) can be extended to cover ranges from 20 to 100 km by replacing the last term log$d$ by $(\log d)^{\alpha}$, where

$$\alpha = 1 + (0.14 + 1.87\cdot 10^{-4} f + 1.07\cdot 10^{-3} h_t)\cdot[\log(d/20)]^{0.8} \qquad (37)$$

Numerous other path loss models have been proposed, and a few are mentioned in the next paragraph. Many of the following path models have been coded into propagation and coverage programs for PC compatibles.

The Terrain Integrated Rough Earth Model (TIREM) was developed by the National Telecommunications and Information Administration (NTIA) for the Dept. of Defense. At least one commercial implementation of this model is available and provides good results.[12] The Longley-Rice

[12] TIREM is used in the SHDMAP™ and RPATH™ programs developed by EDX Engineering of Salem, OR.

models are popular and implemented in commercial coverage programs. These were originally published by the National Bureau of Standards (now National Institute of Standards and Technology, NIST - see [47]) and are included as a subset of the TIREM model.

CCIR publishes field strength prediction curves in their Recommendation 370-5, which are based on statistical analysis of experimental data in Europe.[59] These curves are widely quoted in a variety of publications for a variety of applications. However, they were originally conceived for interference planning in VHF and UHF television broadcast services and are not suitable for fixed radiotelephone system link design. These curves, in addition to distance and frequency, use the height of the transmitting antenna over the average level of the ground between distances 3 and 15 km from the transmitter toward the receiver. The parameter Δh is used to define the degree of terrain irregularity.

The terrain irregularity factor Δh is one of the many parameters used in the highly detailed propagation prediction method developed by Longley and Rice and described in a landmark report.[46] This report provides FORTRAN code and has been implemented in a number of computerized path analysis programs for the PC.

CCIR Report 567-4 provides a set of propagation curves suitable for predicting coverage of mobile services;[60] however, these curves were derived from those given in Rec. 370-5 and have limited application in fixed system design. Nevertheless, the curves may be useful for planning purposes.

The FCC has used the so-called "Carey Curves" to predict coverage since the 1950's.[26] These curves use the concept of height above average terrain (HAAT) between 2 and 10 mi from the transmitter toward the receiver, which is practically identical to the CCIR method. While the Carey Curves suit the FCC's purposes (and are required by Part 22 in the BETRS licensing process), they do not provide accurate coverage nor do they provide path prediction for fixed systems.

Both the FCC and CCIR curves are based on field strength in dBμv/m. Since most of this monograph uses signal power level in dBm, a conversion chart between the two units is given in Appendix H.

11. K-Factor, Radio Horizon, and Earth's Radius

As ground-waves propagate through the atmosphere, they are curved by the gradual change in the refractive index of air that accompanies an increase in elevation. The index is mathematically related to the dielectric constant of the atmosphere, which determines the velocity of radio wave propagation.

The refractive index ordinarily decreases uniformly with elevation. In this situation, the upper portion of a radio wave-front travels slightly faster than the lower portion causing the radio wave to curve downward. The amount of curvature depends on the rate at which the atmosphere's refractive index changes with height. The refractive index of air depends on the temperature, atmospheric pressure and water vapor pressure. Since the atmospheric processes that affect refractivity take place at a molecular scale, the refractive index is independent of frequency at least to 15 GHz.

The following defines the relationships between the various factors affecting the refractive index:

$$N = (n-1)10^{-6} = \frac{77.6}{T}\left(P + 4810\frac{\rho}{T}\right)\text{N - units} \qquad (38)$$

where n = refractive index, N = radio refractivity index in N-units, T = absolute temperature in Kelvins, P = atmospheric pressure in millibars, ρ = partial pressure of water vapor in millibars. A "normal" atmosphere yields a value of n = 1.0003.

The relative dielectric constant ε_r of the atmosphere is given by:

$$\varepsilon_r = n^2 \qquad (39)$$

Curvature of the radio path and the earth's surface is illustrated in Fig. 14(a). This illustration shows the earth at its true radius with a straight line-of-sight optical path and curved radio path due to refraction.[13]

Radio path curvature usually is measured in multiples of the earth's radius. Thus, any calculation based on such curves may be simplified by multiplying the earth's radius by some constant, called K-factor, that will cause the radio wave to appear as a straight line. This is shown in Fig. 14(b) with a K-factor of 4/3. In this case, the radio path is a straight line and the optical path is curved upwards. A K-factor of 1.0 indicates a radius the same as the physical earth radius (6,370 km or 3,960 mi). An infinite K-factor indicates a flat earth (no curvature whatsoever).

The radio refractivity gradient dN/dh within several hundred m of the ground usually is constant for normal atmosphere and amounts to dN/dh = –39 N-units/km, where h = height above the earth's surface. It is convenient to categorize different atmospheric conditions by the vertical refractivity gradient and to assign K-factors to them. The resulting "radio atmospheres" are given in Table 5. K-factor and dN/dh are related by:

[13] The optical path is refracted slightly, also, but the effect is not as pronounced as on the radio path.

$$KR_e = \frac{10^{-6}}{(157 + dN/dh)} \text{ km} \tag{40}$$

where R_e = true earth radius = 6,370 km.

Table 5
Radio Atmosphere Categories

Atmosphere Type (other common terms)	dN/dh	K-Factor
Subrefractive (substandard, obstruction fading, earth bulge)	79	2/3
Constant	0	1
Normal (standard)	–39	4/3
Super-refractive (super-standard)	–157	∞
Ducting (multipath, overreach, trapping)	–393	–2/3

The K-factor depends on the weather conditions. Generally, where the antennas are greater than approximately 300 ft (90 m) above the ground and the transmission path is less than approximately 15 mi (24 km), atmospheric refraction does not significantly bend the radio path from a straight-line path. However, on longer paths with lower antenna heights (which are typical in BETRS applications), the effects of temperature inversion on refraction are frequently noticed.

Weather effects are most noticeable on paths that reach to the edge of the coverage area in terms of received signal level and where there is little or no fade margin built into the path. The effects of weather on propagation usually are less noticeable (but still significant) in the 150 MHz band than in the 450 MHz and 800 MHz bands. Water vapor (specifically, rain) has no effect on propagation loss below 6 GHz. However, stratified atmosphere or other refraction anomalies may be associated with rainfall, and these affect the propagation path curvature and path fading.

Nocturnal radiation cooling of humid air next to the ground can cause a temperature inversion and a layer of ground fog. This causes refraction to vary abnormally with elevation and gives a *subrefractive* atmosphere. Similarly, when humid air moves over dry air next to the ground (called *advection*) a subrefractive atmosphere results because humid air has a refractivity index that is considerably higher than for dry air. The associated K-factor for a subrefractive atmosphere is 2/3.

A subrefractive atmosphere is relatively unstable because denser air is on top of lighter air. This condition occurs frequently over large bodies of water. Also, refraction is subject to diurnal effects and the movement of weather fronts through the propagation path. Again, for short paths, these effects are not as pronounced as for long paths.

Where the refractive index initially increases with height and then starts to decrease per normal atmosphere, ducting or trapping of the radio waves occurs. This is called a *super-refractive* atmosphere, where dN/dh = –157 N-units/km, or *ducting* atmosphere, where dN/dh = –393 N-units/km. In either case, very humid air (high N) close to the ground is covered by warmer, much dryer air (low N) above. The K-factor is ∞ for super-refractive and –2/3 for a ducting atmosphere.

High humidity levels occur near the ocean surface due to evaporation. Also, cool, dry air will descend from higher regions and cover colder, more humid air next to the ground (a process called *subsidence*). Radiation cooling at night will cause a temperature inversion that produces heavy, cold air below and lighter, warm air above leading to an enhanced negative refractivity gradient. A super-refractive atmosphere generally is more stable than subrefractive.

In a *ducted* path, the radio wave is effectively trapped as it is alternately bent toward the earth and then reflected much like a bouncing ball thrown across a flat surface. Ducting can extend the radio horizon considerably beyond what would be expected under normal conditions. Ground based ducts may rise to higher elevations when the ground is heated by the rising sun in the morning. An elevated duct can cause total internal reflections at both upper and lower extremes.

To summarize, ducts close to the ground are produced by

- A mass of hot, dry air arriving over cold, wet ground or the sea
- Night frosts which cause ducts during the second half of the night
- High humidity next to the ground.

It has been reported that long distance VHF propagation (that is, over-the-horizon) takes place along lines of equal barometric pressure and that pronounced high pressure areas (30.1 in Hg or over) bring improved VHF propagation.[30] These propagation conditions persist only as long as the associated weather conditions persist and, therefore, cannot be used for reliable BETRS service. However, if these or other ducting conditions occur during a site survey or test of a long path, the results may be too optimistic for reliable, everyday service, and the path may be marginal or useless most of the time.

In general, the received signal level is relatively stable during the day, subject to normal fading variations of ±5 to ±10 dB. These variations are due to interference between the direct- and reflected-waves as well as interference between two or more separate paths in the atmosphere. Large and rapid changes in the refractive index occur at night (and are particularly severe on clear nights) and can lead to fades in the order of 20 to 30 dB. It is interesting to note that when these deep fades are occurring, the *average* signal level normally is higher than under stable signal conditions.

The onset of diurnal effects is measured in hours while the fades themselves are measured over periods of minutes or tens of minutes. This tends to explain the common observation on calls over long paths that one call may be entirely satisfactory while another call a half-hour later is unsuccessful or excessively noisy (low signal-to-noise ratio).

The K-factor is considered to be independent of frequency and may vary between 0.8 and 3.0 with a value of 1.33 (4/3 earth radius) generally in agreement with conditions found to exist in the atmosphere 50% of the time in most places. The radio horizon is the point at which a radio path is tangent to the earth. With a 4/3 earth radius, the radio horizon is beyond the optical horizon as previously shown.

While a K-factor of 4/3 is used in most radio propagation work, the path should be analyzed for other values where anomalies or seasonal variations are known or suspected to exist. Fig. 15 shows the measured K-factor for Fairbanks, AK as determined from tests conducted in the late 1950's and early 1960's. Fig. 16 shows the same for Nome, AK.

While these measurements were taken under a limited set of conditions, there is no reason they cannot be used in everyday propagation work. It is fortuitous that K-factor varies little throughout the year in these two areas, as seen from the charts. Also, the K-factor values for Nome can be considered representative of the western and northwestern coasts of Alaska, and the values for Fairbanks can be considered representative of interior Alaska.

No similar data is known to be published for southcentral, southwestern (Aleutian Islands and Bristol Bay), or southeastern Alaska. However, anomalous propagation is known to exist, and should be expected due to large and rapid weather changes, in the Aleutian Islands.

Fig. 14
Radio Propagation Path

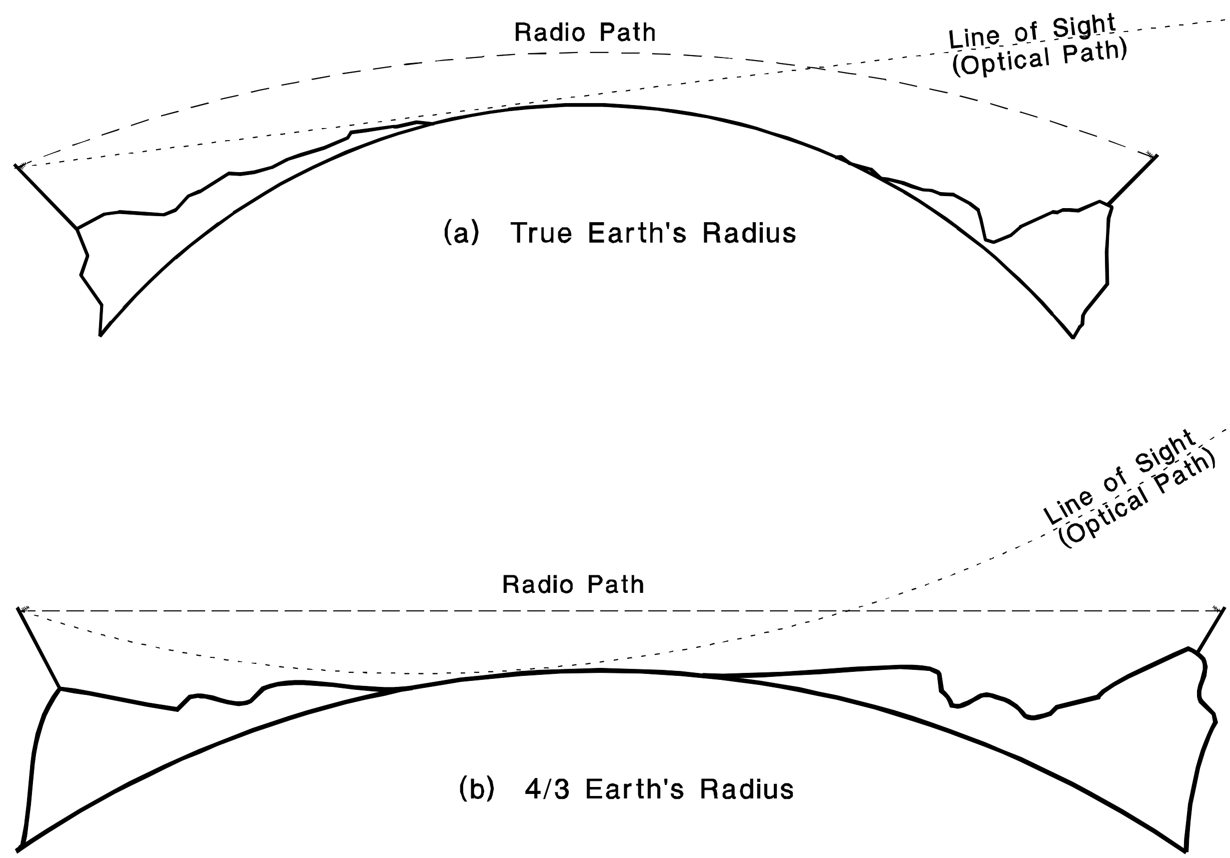
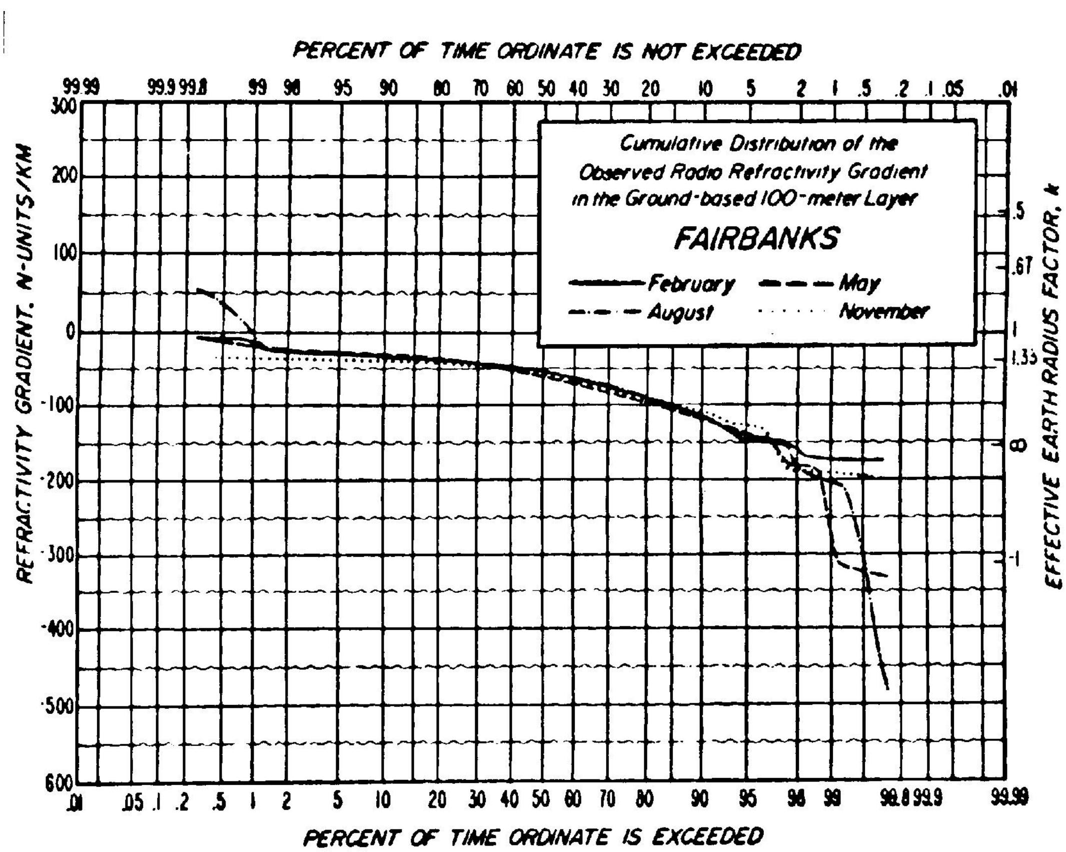


Fig. 15
K-Factor for Fairbanks, AK
Source: [20]



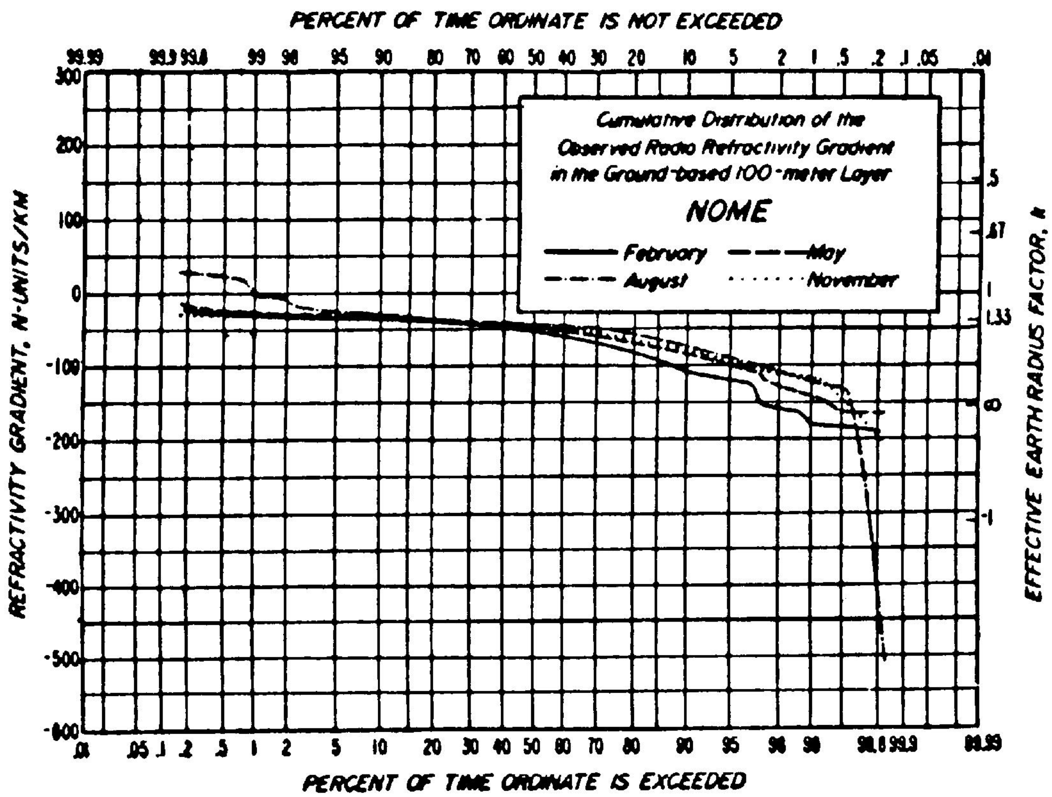
Positive values of the K-factor cause objects, such as trees or terrain, between the transmitter and receiver to be raised from their height determined for an infinite earth radius (flat earth). The amount of vertical height change from a flat earth can be found from

$$h = \frac{d_1(mi)d_2(mi)}{1.5K}\ \text{ft}$$
$$h = \frac{d_1(km)d_2(km)}{12.75K}\ \text{m} \qquad (41)$$

where h = change in vertical distance from the horizontal reference line, d_1 = distance from a point to one end of the path, d_2 = distance from the same point to the other end of the path, and K = equivalent earth radius factor. Use mi in the first expression and km in the second expression for distances. For K = 4/3, the corresponding expressions are:

$$h(K = 4/3) = \frac{d_1(mi)d_2(mi)}{2} \text{ ft}$$
$$h(K = 4/3) = \frac{d_1(km)d_2(km)}{17} \text{ m} \qquad (42)$$

Fig. 16
K-Factor for Nome, AK
Source: [20]

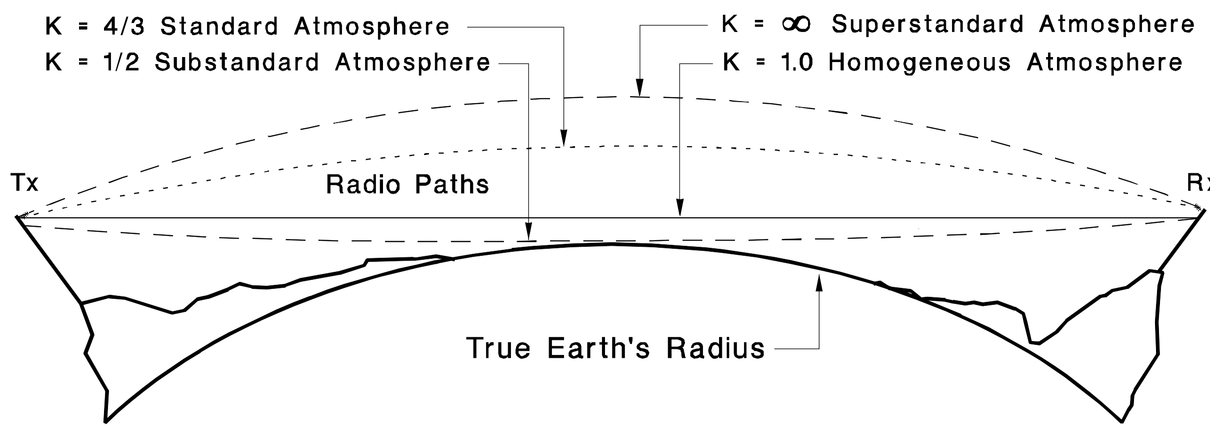


In the middle of a 25 mi path ($d_1 = d_2 = 12.5$ mi), for K = 4/3, an object is raised approximately 78 ft above the height of that same object for K = ∞ (flat earth). For K = 1.0, the object is raised approximately 104 ft above a flat earth. If a K-factor of 1.0 is taken as the reference (rather than flat earth), objects are raised or lowered for other values of K. For a K > 1.0 earth radius, objects are lowered and, for K < 1.0, objects are raised with respect to the vertical distance at K = 1.0.

Fig. 17 illustrates refraction for various values of K on a true earth radius profile. Note that the propagation path for K = 1.0 is a straight line when drawn on a profile with true earth radius. Appendix B describes how to plot a path profile for different values of K.

In most propagation work, only two values of K need to be investigated; these are K = 1.0 and 4/3, with 4/3 usually receiving the most attention. However, where anomalous propagation is known to exist, other values have to be considered. Once a particular K-factor is chosen, it must be determined if the height of objects along the propagation path impinge on the first Fresnel zone radius of the radio wave.

Fig. 17
Propagation Paths for Different K-Factors



An object low enough to provide a full first Fresnel zone clearance (1.0 F_1) for K = 4/3 may block the actual propagation path if conditions change such that K = 1.0. On the other hand, if an object has enough clearance for K = 1.0, it will have more than enough clearance for K = 4/3. An impingement of 0.4 to 0.5 F_1 (leaving 0.6 to 0.5 F_1 clear) at K = 4/3 normally is considered acceptable for VHF and UHF propagation. For a total coastal path, a 0.3 F1 clearance at K = 1/3 may be required due to weather conditions.

Fixed point-to-point microwave radio systems have specific clearance criteria depending on the required path reliability. These are given below. Since an individual BETRS link serves only one subscriber, it normally would be considered approximately the same as a "light route."

Heavy-route, or highest reliability systems:

> At least 0.3 F1 clearance at K = 2/3 and at least 1.0 F1 clearance at K = 4/3, whichever requires the greater heights. (In areas of very difficult propagation, it may be necessary also to ensure clearance of at least grazing at K = 1/2).
>
> Grazing (zero first Fresnel zone clearance) at K = 5/12.
>
> 150 ft direct path clearance at K = 1.0.

Light-route, or medium reliability systems:

> At least 0.6 F1 clearance at K = 1.0 for frequencies 2 GHz and below and at least 0.6 F1 + 10 ft clearance at K = 1.0 for frequencies above 2 GHz.

Other clearance requirements are used in point-to-point microwave radio systems and are summarized here for reference:

Line-of-sight optical clearance at $K = 7/6$.

Grazing at $K = \infty$.

12. Modulation

The FCC uses the term emission to describe the transmitted signal characteristics, which includes bandwidth, modulation type, and modulating signal characteristics. BETRS systems are automatically authorized the following emission designators:

- 15K0F2D
- 16K0F3E
- 16K0F3C
- 16K0F1D
- 16K0F1E

These designators includes four parts as follows: The first four characters indicate the bandwidth with K meaning kHz. In the case of 16K0, the bandwidth is 16.0 kHz. The fifth character indicates the type of modulation. The letter F indicates frequency modulation, or FM. The sixth character roughly indicates the highest modulating frequency in kHz but more accurately is the nature of the modulating signal. The 1 indicates a single channel containing quantized or digital information without a modulating subcarrier. The 2 indicates the same as 1 except it has a modulating subcarrier. The 3 indicates a single channel containing analog information (such as voice or modem tones). Finally, the seventh character indicates the type of information to be transmitted. For C, D and E, the types are facsimile, data transmission or telemetry, and telephony, respectively. Analog BETRS use 16K0F3E emission.

The above authorizations automatically allow frequency modulation exclusively. This does not mean other modulation types cannot be used. However, if anything other than FM is to be used, prior FCC approval is required. This prior approval requirement applies to the phase modulations used in digital BETRS systems and is routinely granted by the FCC.

Frequency modulation is a specific type of the more general angle modulation. FM has three readily defined characteristics - carrier frequency, modulating wave and deviation. Carrier frequency is the output of a transmitter when the modulating wave is zero. The modulating wave contains the actual information to be transmitted, such as voice or modem tones. Deviation is the change in the carrier frequency due to modulation.

FM is said to occur when a carrier frequency is caused to vary from the unmodulated value by an amount determined (usually linearly) by the instantaneous amplitude of the modulating signal, and the amplitude of the carrier remains constant. The maximum modulating signal amplitude determines the maximum carrier deviation. The frequency of the modulating signal determines the rate of change of the carrier frequency.

The relationship between the transmitted signal bandwidth and the deviation of the carrier is mathematically complex. Theoretically, the bandwidth is infinite; however, according to Carlson's Rule, most of the usable information is contained within a bandwidth given by:

$$BW = 2(\Delta f + f_m)\,\text{kHz} \tag{43}$$

where Δf = the deviation in kHz and f_m = the highest modulating frequency in kHz. The FCC limits the deviation in BETRS systems to ±5 kHz, and f_m normally is considered to be 3 kHz as limited by filters in the transmitter's modulator. Therefore, the bandwidth for BETRS systems is 2(5 + 3) = 16 kHz. The performance of FM systems is directly related to the bandwidth as discussed in the next section.

As mentioned above, digital modulation methods may be used with BETRS. Presently, there is only one company actively marketing digital BETRS equipment, although there are installed systems by at least one other manufacturer.[14] The currently marketed system uses multi-level Differential Phase Shift Keying (DPSK) in which the presence of a binary one or zero is manifested by the symbol's similarity or difference when compared to the preceding symbol. Either 4-ary or 16-ary DPSK is used depending on the selected voice channel encoding rate.

One of the benefits of digital modulation is the system can operate at a significantly lower carrier-to-noise ratio (or, stated another way, for a given noise can operate at lower transmitter power).

In DPSK modulation, the analog voicegrade channel is first converted to a 64 kb/s pulse code modulated (PCM) digital signal using an analog-to-digital converter. The 64 kb/s signal is then compressed and groups of two bits (4-ary DPSK) or four bits (16-ary DPSK) are used to shift the phase of the carrier frequency with respect to the phase of the previous signaling interval. The compression of the 64 kb/s PCM representation of the original voiceband signal results in a 32 kb/s (4-ary DPSK) or 16 kb/s (16-ary DPSK) digital rate.

With this compression, either two or four voice channels are combined and then used to modulate the carrier of one RF channel at a 64 kb/s rate. Therefore, the digital modulation methods provide circuit gains of either 2:1 (4-ary DPSK) or 4:1 (16-ary DPSK) when compared to narrowband analog modulation methods, which only are capable of supporting one voicegrade channel per RF channel.

At the receiver, the phase difference of the carrier is detected (with respect to the previous symbol). The resulting digital bit stream is expanded and converted by a digital-to-analog converter to the original analog voicegrade signal.

The currently available digital BETRS system uses 20K0G1E emission. The first four characters mean each RF channel has a 20.0 kHz bandwidth. The G indicates phase modulation, and the following 1 and E characters indicate a channel with quantized digital information without a modulating subcarrier used to carry telephony information.

The other digital BETRS system not actively marketed but mentioned above uses either 8-ary or 32-ary Quadrature Amplitude Modulation (QAM). This system encodes each voice channel at the 64 kb/s rate, which either can be compressed to 32 kb/s or left alone to modulate a carrier in both amplitude and phase. With compression, a circuit gain of 2:1 results. The FCC emission designator for the QAM system is 20K0D7W. The first four characters indicate 20.0 kHz bandwidth. The D indicates an amplitude and phase modulated carrier. The last two characters 7 and W indicate two or more channels of quantized digital information with a combination of telephony, data transmission and other information.

---

[14] Inter-Digital Corporation *UltraPhone®* and Alcatel CXR-424, respectively.

Channel spacing is the minimum frequency spread between any two adjacent transmitter carrier frequencies in a system. Channel spacing takes into account the transmitted bandwidth, modulating signal characteristics and type of modulation used. The spacing always is greater than the signal bandwidth to provide a guard band which accounts for transmitter and receiver frequency tolerances, imperfect filters and equipment variations. Channel spacing in the 150 MHz band is 30 kHz and for the 450 and 800 MHz bands is 25 kHz.

13. Transmitter and Receiver Performance

Transmitters used in BETRS applications have a few watts to a few tens of watts power output and receivers have 0.5 μv sensitivity. Appendix B gives the transmitter output power in dBm and watts and the receiver sensitivity in dBm for various BETRS equipment commonly used in each frequency band. The transmitter power shown is the power available at the antenna connector and is therefore the net of power amplifier output less losses in the duplexer, output filters, combiners and connectors. The total of these losses is approximately 1.5 to 2.0 dB. This is somewhat dependent on operating frequency, but the actual value does not matter as long as the power available at the antenna connector is the value used in path design.

Signal-to-Noise Ratio (SNR) is used to indicate the performance of analog receivers. SNR is a post-detection measurement and is related to Carrier-to-Noise Radio (CNR), which is a pre-detection measurement. The relationship between SNR and CNR depends on the modulating frequency, frequency deviation and bandwidth in FM systems and is nonlinear.

Receiver sensitivity performance usually is given for two measurement conditions, 12 dB SINAD ratio and 20 dB quieting, the latter being more stringent. Test procedures are given in a later section for each measurement.

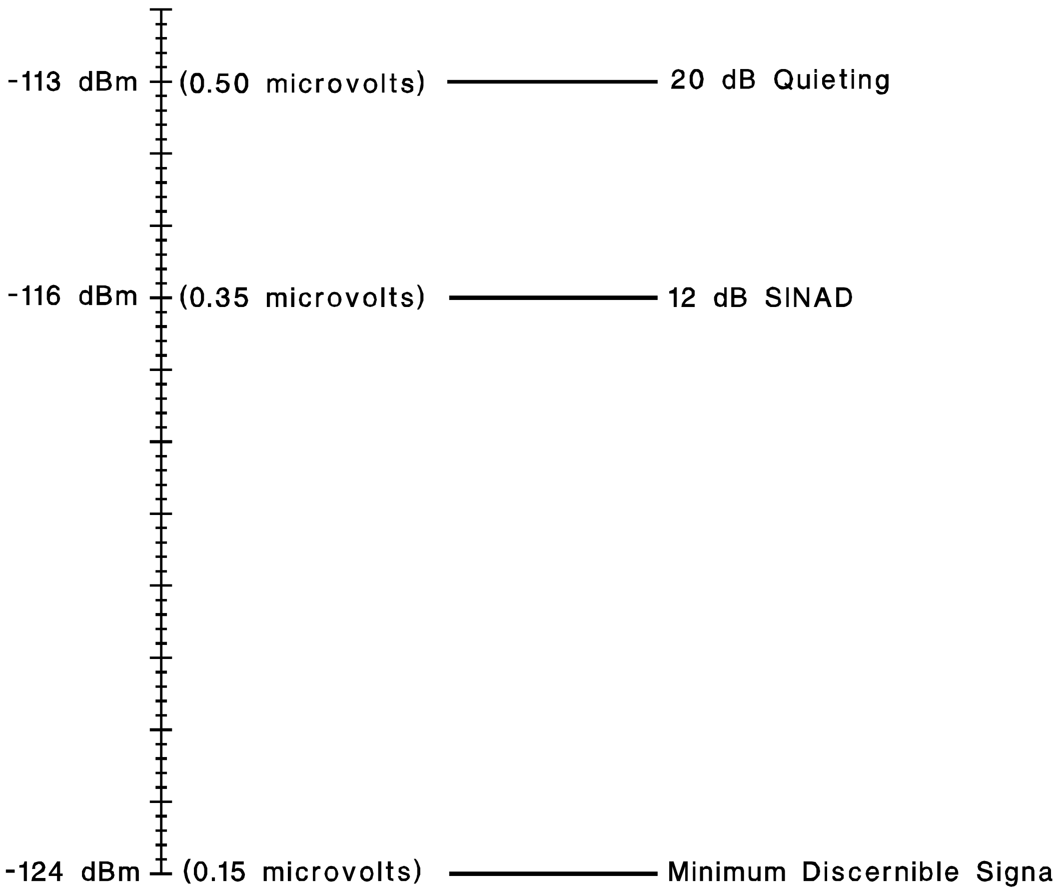
SINAD stands for SIgnal plus Noise And Distortion (the actual ratio measured is signal + noise + distortion to noise + distortion) and is a measurement used in mobile radio specifications. On the one hand, paths designed to provide the 12 dB SINAD level normally should *not* be used in BETRS applications because a subscriber would perceive a circuit with 12 dB SINAD performance as noisy. However, the 12 dB SINAD performance level may be acceptable during worst-case fading conditions that are encountered a small percentage of the time.

On the other hand, the subscriber would perceive a circuit with 20 dB quieting performance as acceptable. In analog FM systems, there is some perceived performance improvement with higher SNR above the 20 dB quieting level. However, for propagation conditions that persist for the majority of the time, the receiver signal input level for 20 dB quieting (plus adequate fade margin) is a good design goal.

Fig. 18 shows the relationship between the 12 dB SINAD, 20 dB quieting and minimum discernible signal (MDS) level in a typical narrowband FM receiver. The MDS is the point where the noise power equals the signal power (0 dB SNR).

FM systems exhibit a threshold as the carrier-to-noise ratio (CNR) approaches 9 or 10 dB. CNR is a pre-detection value normally referred to the intermediate frequency amplifier in the receiver. SNR, on the other hand, is a post-detection value referred to the output of the baseband detector (FM discriminator in analog FM radios).

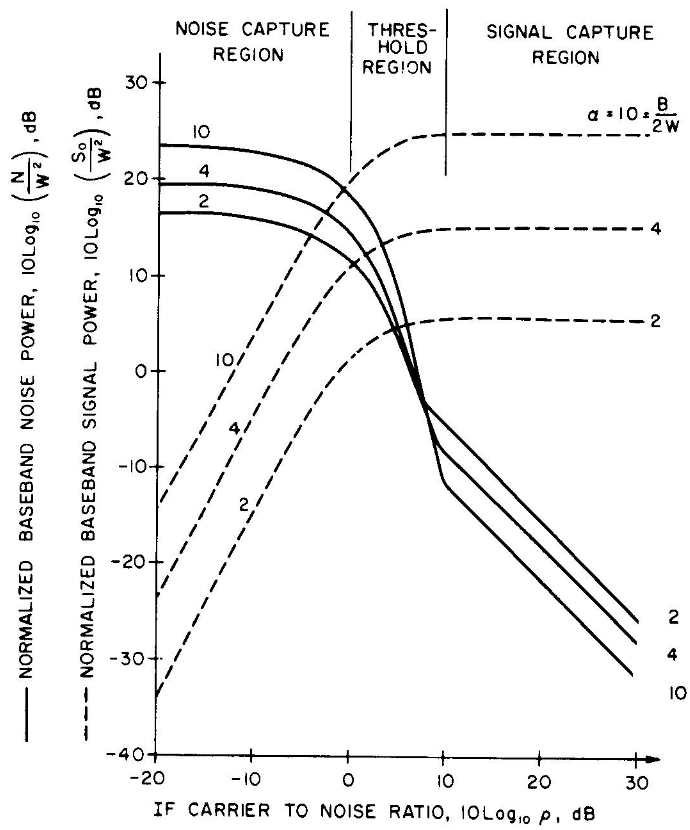
Fig. 18
Typical Narrowband FM Receiver Performance



At low CNR (below approximately 9 or 10 dB), the signal is masked by the receiver noise. At the threshold, the modulated carrier peaks and the noise peaks are the same level and the SNR suddenly exceeds the CNR. Conversely, as the CNR falls below the threshold, the baseband noise increases rapidly. This threshold effect sometimes is described in terms of "clicks," which are heard as the noise or signal rapidly changes at the threshold.

The threshold region is illustrated in Fig. 19. On a rising CNR, the noise predominates in the "Noise Capture Region" but starts to decrease rapidly at CNR = 0 in the "Threshold Region." At the same time, the signal is rising but starts to level off in the "Threshold Region" and then predominates at a constant value in the "Signal Capture Region." For BETRS systems, the value of α (B/2W) is 3 to 4. In a heavy and fast fading environment (such as encountered in mobile applications), this sudden increase in SNR is not so apparent.

Fig. 19
Noise Quieting and Signal Suppression Effect in Analog FM Systems
Source: [9]



Assuming CNR > 9 dB, the relationship between SNR and CNR for FM systems is given by:

$$SNR = 10\log\left[CNR\left(\frac{3}{2}\frac{\Delta f_{rms}^{\ 2}}{f_m^{\ 3}}\right)\right] = 10\log\left[\left(\frac{P_r}{KT_0F}\right)\left(\frac{3}{2}\frac{\Delta f_{rms}^{\ 2}}{f_m^{\ 3}}\right)\right] \tag{44}$$

where P_r = receiver input power in watts, K = Boltzmann constant (1.38E-23 Joules/Kelvin), T_0 = temperature (normally 290 to 300 Kelvins), F = receiver overall noise figure as a linear value (not dB), Δf_{rms} = rms frequency deviation in Hz, f_m = highest modulating frequency in Hz (normally 3,000 Hz). Equation (44) assumes all noise is thermal noise and does not include interference noise from co-channel systems. Note that:

$$\beta = \frac{\Delta f_{rms}}{f_m} \tag{45}$$

where β = modulation index. The expression for SNR (eq. 44) can be rewritten as:

$$SNR = 10\log(P_r) - 10\log(F) + 10\log(M) \text{ dB} \tag{46}$$

where

$$M = \frac{3}{2KT_0}\frac{\beta^2}{f_m} \tag{47}$$

Manufactures normally do not provide the noise figure F on their data sheets, but it is around 8 dB for typical FM receivers used in BETRS applications.[15] Better and worse values will be encountered in the field. The noise figure and IF bandwidth B determine the effective noise and threshold input to the receiver. The effective noise input to the receiver is:

$$P_n = 10\log(KT_0BF)\,\text{dBW} = 10\log(KT_0BF) + 30\,\text{dBm} \tag{48}$$

where P_n = noise power expressed in terms of the input and B = IF noise bandwidth in Hz. For BETRS receivers using analog FM, B = 16 kHz. To be used properly in this expression, F must be a linear value (not dB). If the noise figure is given in dB, it may be converted to a linear value by (the square brackets indicate the value in dB):

$$F = 10^{[F]/10} \tag{49}$$

The minimum receiver input threshold level, P_{th}, is:

$$P_{th} = P_n + 9\,\text{dB} \tag{50}$$

where the constant 9 dB is sometimes replaced with 10 dB. For any given received level, the CNR is:

$$CNR = P_r - P_n\ \text{dB}. \tag{51}$$

The peak frequency deviation, Δf_p is specified by the FCC in Part 22 to be no more than 5 kHz. The deviation is proportional to the amplitude of the modulating signal, f_m. The rms value of a voice modulating signal typically is 10% of peak, but compandoring approximately quadruples the rms to 40% of peak. Then, with compandoring, the rms deviation on a typical voice call is around (40% X 5 kHz =) 2000 Hz. For modem calls the rms deviation will typically be greater because the rms amplitude is greater. BETRS transmitters normally are adjusted for 1.5 to 2.5 kHz deviation with a 0 dBm, 1 kHz test tone at the 2-wire telephone input port.

It can be seen that a higher SNR is obtained with higher deviation. Technicians sometimes adjust the deviation above the manufacturer's recommended test values to compensate for marginal radio links, but this is not recommended for obvious reasons. In other words, transmitter modulation adjustments should not be used to compensate for poor link design.

As an example of an SNR calculation, consider the following situation. The receiver input power is found to be -137 dBW (-107 dBm) from one of the path loss models. This includes all antenna gains

[15] This value does not take into account the transmission line loss between the antenna and the receiver. The line loss must be added to the receiver noise figure to obtain the overall noise figure for the receiving system.

and line losses and is assumed to be an average value with no fade margin. Assume the receiver noise figure is 8 dB (6.3 linear) and Δf_{rms} = 2 kHz. In this case, β = 2 kHz/3 kHz = 0.67, and

$$SNR = -137\text{ dBw} - 8\text{ dB} + 167.3\text{ dBw} = 22.3\text{ dB}.$$

The threshold input power for this receiver (assuming no co-channel or adjacent channel interference) is

$$P_{th} = 10\log\left(KT_0BF\right) + 9\text{ dB} = -144.8\text{ dBw} = -114.8\text{ dBm}$$

and

$$CNR = P_r - P_n = 16.8\text{ dB}.$$

Note in this case, SNR is greater than CNR by 5.5 dB. The difference is highly dependent on the transmitter deviation. The foregoing link probably would be acceptable for the average call. However, a subscriber using this link over a period of time may eventually complain of dropped calls, noisy calls or inability to dial due to multipath fading. A high quality link will provide a 30 dB SNR on the average with a 15 to 20 dB fade margin. This fade margin gives around 90% or better reliability; a 20 to 25 dB fade margin gives around 99% reliability. See Table 3.

In systems using digital modulation, it is more convenient to use the bit energy per noise power spectral density, or E_b/N_0, rather than SNR. The two are related by

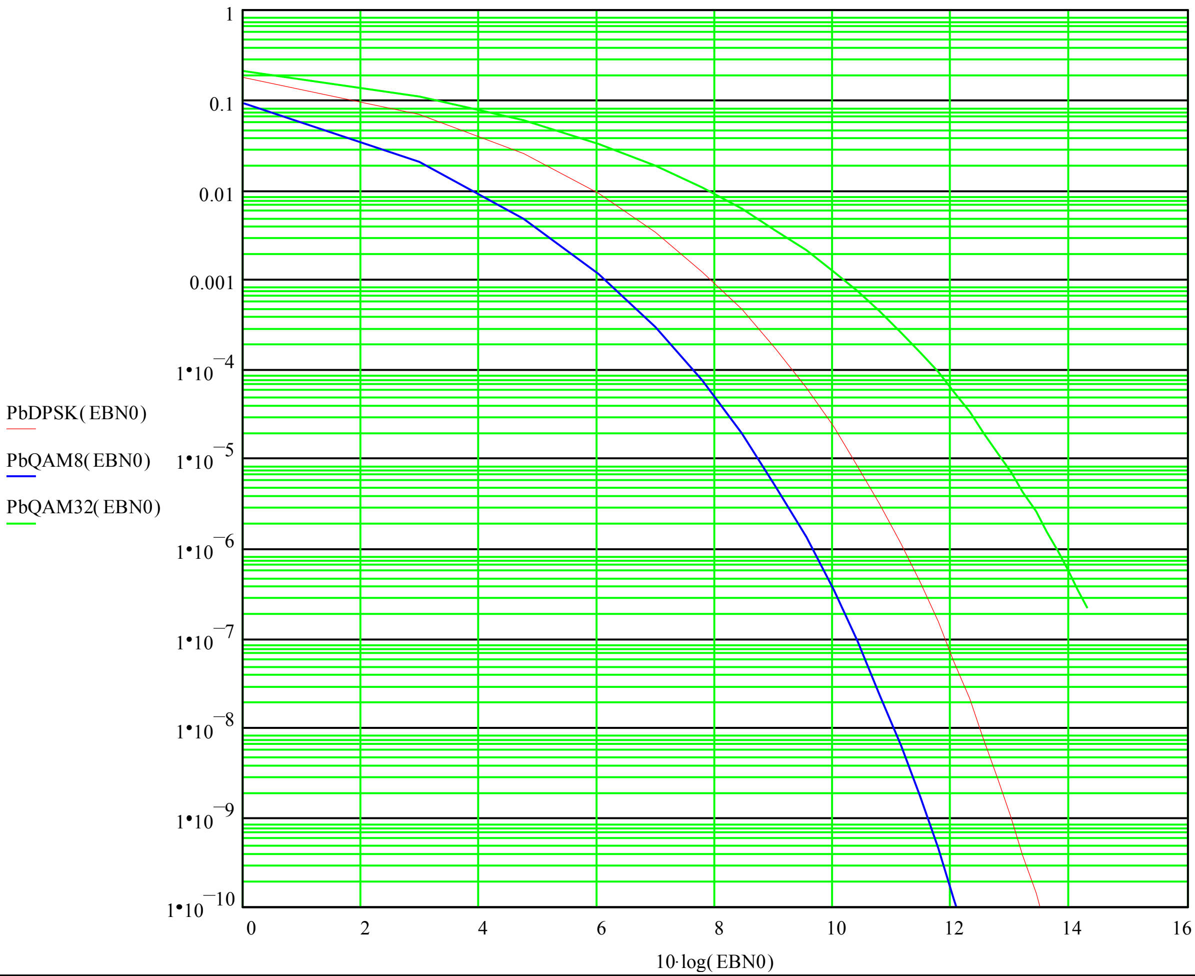
$$\frac{E_b}{N_0} = \frac{S}{N}\left(\frac{B}{R}\right) \qquad (52)$$

where S = average signal power, N = average noise power, B = bandwidth in Hz, and R = bit rate in b/s. In this equation, the rate R actually is higher than 64 kb/s because additional overhead is added for forward error correction (FEC) and signaling (giving around 70 kb/s total rate).

DPSK systems provide BER = 1E–6 at an E_b/N_0 of around 11.2 dB and for BER = 1E–4, E_b/N_0 is around 9.3. A 1 dB change either way changes the BER approximately by a factor of 100 at the lower BERs. Because of error correction, it is possible to operate the digital BETRS systems at higher BER than otherwise would be required. The probability of bit error for DPSK is given by equation (53) and plotted in Fig. 20 (designated PbDPSK).

$$P_b = \frac{1}{2}\exp\left(-\frac{E_b}{N_0}\right) \qquad (53)$$

Fig. 20
Bit Error Probability vs E_b/N_0 (dB) for DPSK, 8-ary QAM and 32-ary QAM



Similar information for 8-ary and 32-ary QAM follows: For a BER = 1E–3, 8-ary and 32-ary QAM require an E_b/N_0 of about 6 dB and 10.1 dB, respectively. For BER = 1E–6, E_b/N_0 is approximately 9.6 and 13.8 dB, respectively. The probability of bit error for QAM is given by equation (54) and plotted in Fig. 20 for 8-ary QAM (designated PbQAM8) and 32-ary QAM (designated PbQAM32).

$$P_b = \frac{2}{\log_2(l)}\left(1-\frac{1}{l}\right)\text{erfc}\left[(\log_2 l)^{\frac{1}{2}}\left(\frac{6}{l^2-1}\right)^{\frac{1}{2}}\left(\frac{E_b}{N_0}\right)^{\frac{1}{2}}\right] \qquad (54)$$

where $l = \sqrt{M}$ (M = 8 for 8-ary QAM and M = 32 for 32-ary QAM).

With multi-level digital modulation (where M is the number of levels), a symbol is used to represent a group of bits. For example, with 4-ary signaling, a symbol represents two bits and with 16-ary signaling, a symbol represents 4 bits. It is common to use a binary-to-M-ary code such that binary sequences corresponding to adjacent symbols (phase shifts) differ in only one bit position. When an

M-ary symbol error occurs with this arrangement, it is more likely that only one of the input bits in that symbol will be in error. Therefore, the occurrence of a multi-bit error, for a given symbol error, is much reduced. For DPSK, the symbol error rate is related to the bit error rate by:[16]

$$P_s = (\log_2 M)\,P_b \tag{55}$$

where P_s = symbol error rate, P_b = bit error rate, and M = number of levels in the modulation. For QAM, the symbol error rate and bit error rate are related by:

$$P_s = (\log_2 l)\,P_b \tag{56}$$

In both digital BETRS systems previously discussed in the previous section, the actual receiver threshold sensitivity depends on the number of modulation levels used and is slightly different than given above (which is based on theoretical considerations). The higher the number of modulation levels, the higher the threshold. In the DPSK system, moving from 4-ary to 16-ary DPSK requires 12 dB higher threshold for a BER of 1E–4. In the QAM system, moving from 8-ary to 32-ary QAM requires 7 dB higher threshold for a BER of 1E–6.

To find the digital receiver threshold, the formulations for analog FM receivers are changed to include the bit energy per noise power spectral density and bit rate. The digital receiver exhibits somewhat of a threshold effect at approximately $E_b/N_0 = 0$. As E_b/N_0 increases further, BER rapidly decreases. However, operation at $E_b/N_0 = 0$ is not possible with the BETRS systems being discussed; for these systems a threshold level giving the required BER (usually 1E–4 or 1E–3) is used. The digital receiver threshold is given as

$$P_{th} = P_n + 10\log\left(\frac{E_b}{N_0}R\right)\text{dB} \tag{57}$$

where P_n is the same as was previously given for the analog FM case. The overall noise figures for digital receivers are about the same as for analog FM receivers. It can be seen from the steepness of the bit error probability curves that if a digital system is operated close to its threshold levels, fading could cause a dropped call due to intolerably high BER.

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[16] Note: $\log_2(x) = \log_{10}(x)/\log_{10}(2)$.

14. Antennas and Antenna Supporting Structures

The antenna system, including the antennas, their supporting structures and transmission lines, will make or break a BETRS system. No shortcuts should be made in the design, purchase, installation and maintenance of these elements. This section describes the considerations necessary for proper design and construction; the next section describes transmission lines.

The objective of any BETRS system design is to locate the antennas where they are high enough to provide adequate signal strength at all expected receiver locations and low enough to be built economically. However, the antennas (central office station antenna at the central office and the subscriber station antenna at the remote subscriber's location) rarely are optimally located for a variety of reasons - mostly cost.

The central offices where the BETRS systems are installed usually were built long before the BETRS system, and no thought was given to optimizing the location for propagation. Nevertheless, the central office station antenna usually is built on a relatively higher supporting structure (tower) but, due to cost or other considerations, still may not be at an optimum height. A minimum height of 16 m (50 ft) to the highest point on the antenna is desirable in point-to-multipoint applications. This height is achievable at reasonable cost. Antennas for point-to-point applications generally are lower simply because they usually are installed on short notice and without the benefit of detailed engineering analysis (and the lower height may be adequate, anyway).

The Federal Aviation Administration must be notified if an antenna or antenna supporting structure may pose a hazard to air navigation. It always is best to err on the side of conservatism if some doubt exists if the structure poses a hazard. The FAA is notified by submitting a completed FAA Form 7460-1 to the FAA Alaska Region office. The FAA may require marking or lighting of the structure. The FAA requirements are given in their Advisory Circular AC-70/7460-1H.[41] The FCC covers essentially the same information in Part 17.[43][17]

Low antenna heights, at either the central office or subscriber stations, result in obstacles and reflecting surfaces in the vicinity of the antenna. These, in turn, have a substantial influence on the characteristics of the propagation path. Increasing (or decreasing) the antenna heights affect the received signal level. Generally, for heights < 5 m, the signal changes by 3 dB/octave of height change.[18] For heights > 10 m, the signal changes by 6 dB/octave. For heights between 5 and 10 m, the correction linearly increases from 3 to 6 dB/octave. A decrease in height results in a decrease in received signal and an increase in height results in an increase in signal level.

As an example, consider a system *design* based on a central office station antenna height of 16 m. When this station is *built*, however, the antenna is placed at 8 m. The foregoing information indicates the expected received signal will be somewhere between 6 dB and 3 dB less than the original design.

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[17] The details of FAA notification and requirements for marking supporting structures are beyond the scope of this guide but are covered in a future monograph on licensing.

[18] An increase in height of one octave means the height has been doubled; a decrease of one octave means the height has been halved.

Depending on the geographical area and directions to be covered, either an omni-directional antenna or directional antenna may be used at the central office station. In both cases, as high of gain as possible should be used to maximize the signal received at the other end of the link. Directional antennas, specifically relatively inexpensive Yagi antennas with gains of 5 to 10 dBd, are used in point-to-point applications at both ends.

Yagi antennas may be stacked to obtain more gain. When two identical antennas are properly spaced, one on top of the other or side-by-side, and interconnected with a properly cut phasing harness, the gain increase is theoretically 3 dB over a single antenna. This increase is realizable in field installations. For example, if two 10 dBd gain antennas are stacked as shown in Fig. 21(a), the gain of the combination is about 13 dBd.

Installing another pair of identical antennas (total of four) theoretically results in another 3 dB gain increase to a total of 16 dBd. When four Yagis are interconnected to obtain higher gain, they normally are not all stacked vertically but are installed in a 2X2 arrangement as shown in Fig. 21(b).

Regardless of the actual antenna gain, the theoretical gain increase is possible only if all antennas are identical. The antenna physical alignment and phasing cable harness construction is critical, and the gain increases may not be realized in the field except when factory mounts and cable harness are used. In most cases, stacking multiple antennas to increase gain sacrifices bandwidth. It is possible to customize the combined antenna radiation pattern by angular adjustment of the individual antennas or by using different separations. The placement of the antenna on the supporting structure also may affect the radiation pattern.

The nomenclature dBd indicates the gain is measured in decibels with respect to a dipole antenna. A dipole antenna has a gain of 2.15 dB over an isotropic antenna. Therefore, an antenna with gain = 7 dBd has gain = 9.15 dBi. It must be known whether the path loss determined from a particular propagation model is between isotropic or dipole antennas (all path loss models in this guide assume isotropic antennas). The path loss between two dipole antennas is (2 X 2.15 =) 4.3 dB less than between two isotropic antennas.

It generally is not advisable to use the gain values given in manufacturer's sales literature without first examining gain charts or polar plots produced from actual tests. If actual test records are not available, it usually means the manufacturer has not actually tested the antenna. In this case, another manufacturer or another antenna should be selected.

Higher gains are possible with individual Yagi antennas, but very high gain antennas usually do not have the bandwidth necessary for operation throughout the BETRS frequency bands. This normally is not a problem where antennas are used for only one frequency or a narrow band of frequencies. However, consideration must be given to the fact that the transmit and receive frequencies of BETRS systems are separated by 5 MHz or more (depending on the frequency band). An antenna cut for a single frequency operation would be cut at the mid-band frequency given by:

$$Midband\ Frequency = \frac{Tx_f + Rx_f}{2}$$

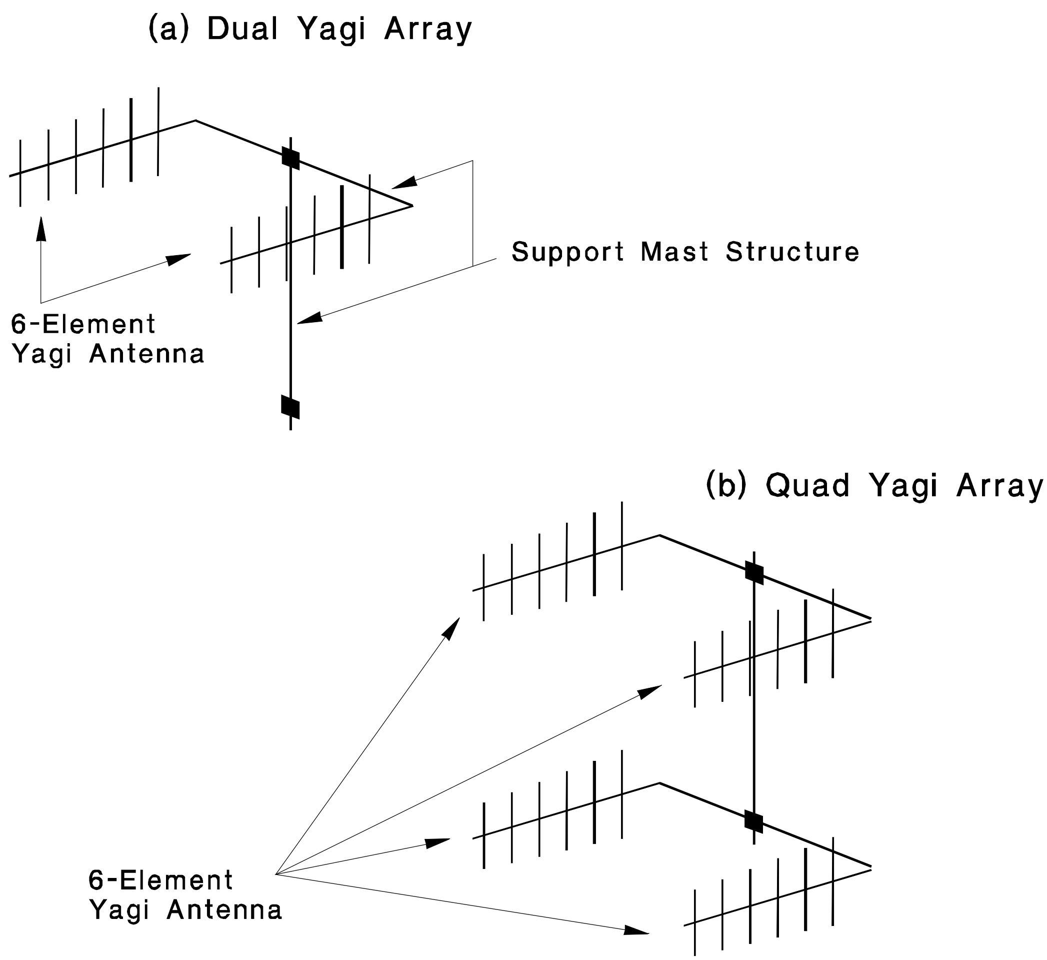
where Tx_f and Rx_f are the transmit and receive frequencies, respectively.

For wideband operation where very high gain is needed, a wideband corner reflector or truncated parabolic antenna is preferred. These have gains of 10 to 19 dBd but are quite large and heavy in the 150 MHz band (typically 10 ft high by 10 ft wide - less in the other bands).

Omni-directional antennas are almost always used in multipoint applications at central office stations, but in some mountainous areas, where subscribers would never be located in certain directions, a directional antenna is a better choice. High gain omni-directional antennas are usually of a collinear design with gains of 7 to 9 dBd.

Subscriber station antennas in both point-to-point and multipoint applications are almost always at relatively low heights because of the cost and difficulty of erecting supporting structures in remote and isolated locations. A minimum subscriber station antenna height of 6 m (20 ft) is desirable and achievable at reasonable cost in areas without significant winds. In windy areas, this height is achieved at higher cost because of the need for strong supporting structures (such as treated wood poles or guyed lattice towers).

Fig. 21
Stacked Yagi Antenna Configurations



Subscriber station antennas always are directional, usually the same Yagi antennas frequently used at the central office station. Parabolic reflector antennas are used where high gains are needed. In some situations, antennas with narrow *beamwidth* and low sidelobes are required to reduce problems with multipath (reflections). Narrow beamwidth antennas also have high gain, and this gain may be so high that receivers are overloaded by the resulting high signal levels. This can be prevented by putting an attenuator in the transmission line between the radio and the antenna. Connected at the antenna port, the attenuator reduces both the received and radiated power and must be rated to handle the transmitter power output.

Where a subscriber station is subject to severe multipath fading, a directional antenna usually is the best choice. However, an antenna with a wide horizontal beamwidth may give better performance than a very high gain antenna because it is desirable to gather as much of the signal as possible, including reflected signals. This is particularly true with fixed analog FM systems, where the delay associated with individual paths has little effect on signal quality. However, reflected signals with significant delay and field strength may result in detection problems in digital systems.

The foregoing information may appear to be conflicting. This indicates the need for actual field measurements or experimentation in situations of high multipath fading.

The combination of antenna gain and transmitter power at the subscriber station determines if the subscriber station must have a separate license. Under normal conditions, the subscriber station is covered by the central office station's blanket authorization. However, if the effective radiated power (ERP) at the subscriber station exceeds 60 watts or the height is such that FAA notification is required as detailed in the FCC rules, the subscriber station is not covered by the central office station blanket authorization, and it *must* have a separate license.[19]

The ERP can be calculated using

$$ERP = P_t - L_t + G_t \text{ dBW} \tag{58}$$

where ERP = effective radiated power (dBW), P_t = transmitter power (dBW), L_t = transmission line loss between the transmitter output connector and the antenna connector (dB), and G_t = transmitter antenna gain (dBd). Note that this equation refers ERP to a dipole antenna. Also, since the equation gives ERP in dBW, it is necessary to convert to watts. Since

$$ERP = 10\log\left[ERP(\text{watts})\right] \text{ dBW} \tag{59}$$

then

$$ERP = 10^{\left[ERP(\text{dBW})/10\right]} \text{ watts.} \tag{60}$$

Finally, many BETRS system specifications give transmitter power in dBm. To convert to dBW, use the following:

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19 See FCC rules, Part 17, for conditions under which FAA notification is required.

$$P_t\,(\text{dBW}) = P_t\,(\text{dBm}) - 30\ \text{dB} \tag{61}$$

As an example, consider the following system: The transmitter power is given as +33 dBm, and the antenna gain is 7 dBd. The line loss is 0.8 dB. Then, $P_t = +33\ \text{dBm} - 30\ \text{dB} = +3\ \text{dBW}$, and $ERP = +3\ \text{dBW} - 0.8\ \text{dB} + 7\ \text{dBd} = 9.2\ \text{dBW}$.

Converting to watts, $ERP = 10^{9.2/10} = 8.3$ watts. If this transmitter and antenna combination is installed at a subscriber station, a separate license would not be required because the ERP < 60 watts.

Next, consider the following system: The transmitter power is 3 watts, and the antenna gain is 15 dBd. The line loss is 1.5 dB. Then,

$P_t = 10\log(3\ \text{watts}) = +4.8\ \text{dBW}$, and $ERP = +4.8\ \text{dBW} - 1.5\ \text{dB} + 15\ \text{dBd} = 18.3\ \text{dBW}$. Converting to watts, $ERP = 10^{18.3/10} = 67.2$ watts. If this transmitter and antenna combination is installed at a subscriber station, a separate license clearly would be required because the ERP > 60 watts. As a rule of thumb, any subscriber station with an ERP > 17.8 dBW (47.8 dBm) requires a separate license. Many combinations of transmitter power, line loss and antenna gain meet this requirement.

In most systems, the same antenna and coaxial cable is used for transmitting and receiving. Therefore, $G_t = G_r$ and $L_t = L_r$.

BETRS system antennas normally are vertically polarized. Physically, this means the radiating elements of the antenna are situated in the vertical plane. The FCC rules require vertical polarization in some land mobile services and horizontal in others. There is some confusion in the industry whether the rules require BETRS systems to be vertically or horizontally polarized. Some applicants for BETRS licenses have requested waiver from the FCC rules to use vertical polarization. However, the rules specifically say "Rural subscriber stations communicating with base stations may employ vertical polarization."[20]

It would be impractical in two-way communications such as BETRS for the subscriber and central office stations to have different polarizations. Therefore, both the central office station and subscriber station antennas can have vertical polarization, and it is not necessary to request a waiver from the FCC rules to use it. All commercial omni-directional antennas in the BETRS frequency bands are vertically polarized. Yagi antennas can be installed with the radiating elements horizontally situated if horizontal polarization is needed. Horizontally polarized omni-directional antennas can be obtained from some manufacturers (or built) if they are needed.

The Electronic Industries Association provides standards for base station and fixed station antennas under RS-329-A, Minimum Standards for Land-Mobile Communication Antennas, Part I - Base or Fixed Station Antennas.[54] However, not all manufacturers build to this standard, and the quality of antennas used in BETRS applications vary greatly among manufacturers. Usually, the radio equipment manufacturer purchases antennas from established antenna manufacturers on an OEM basis and resells

[20] FCC rules, Part 22, par. 22.110(b)(1).

them with a packaged system. At least one BETRS radio equipment manufacturer resells very poorly designed Yagi antennas. These antennas are cheap and they fail soon after being exposed to weather.

With these comments in mind, it is best to separately purchase antennas and, if necessary, purchase them directly from the antenna manufacturers or their distributors.[21] Only manufacturers with quality products are listed in the footnote. Consumer and amateur radio antennas should never be used. The purchase specifications should include the following:

1) *Frequencies (or frequency range) and VSWR* (The same antenna most often is used for both transmit and receive, so it must have the bandwidth to cover both the transmitter frequency range and receiver frequency range. The voltage standing wave ratio (VSWR) should be no worse than 1.5:1 over the specified frequency range. The lower the VSWR, the better.)

2) *Gain* (It should be made clear whether the gain is with respect to an isotropic antenna or dipole antenna. In most situations, the higher the gain, the better; however, higher gain antennas are more expensive than their lower gain counterparts.)

3) *Power handling capacity* (Since most BETRS transmitters are rated at a few watts, or at most a few tens of watts, this is not a critical parameter because all commercial antennas are rated to handle several hundred watts.)

4) *Sealed construction* (This is especially important for the coaxial cable connection at the antenna. The cable provided with the antenna must have provisions for moisture blocking where the cable connects to baluns or antenna elements, which may be inaccessible to the installer.)

5) *Mounting provisions* (Antennas usually are mounted on a pipe support, which, in turn, is fastened to the tower or pole. The mounting hardware provided with the antenna should cover the pipe diameter range used, typically less than 3 in.)

6) *Wind and ice loading* (This is a critical parameter virtually everywhere in Alaska. The usual rating is 125 MPH survival with 1/2 in. of ice. Some coastal areas of Alaska require higher wind and ice rating. High wind and ice loads seldom occur at the same time except in mountain top areas, but it is best to design for the worst case.)

Although item (6) above describes ice loading from a structural perspective, it also is necessary to consider how ice affects antenna electrical performance. Icing can be particularly bad along coastal areas of Alaska, but it is not limited to those locations. It has been shown that Yagi antenna directivity can be reversed by icing.[32] The higher the frequency, the more serious is performance degradation. In the 150 MHz band, the effects may be minimal but in the 800 MHz band may be substantial. Icing reduces antenna bandwidth and distorts radiation patterns. To reduce the effects of icing, the antenna may be enclosed in a plastic case or covering. At a minimum, the fed dipole and the first and second directors should be covered to prevent ice from building up in the air-space between the elements. This will reduce detuning but may not reduce radiation pattern distortion.

[21] Antenna Specialists, Celwave, Decibel Products, and Scala make well-designed antennas for BETRS applications. Radiation Systems (Mark Antennas) makes parabolic antennas for situations where high gain is needed.

Although any given antenna provides equal gain and performance when used as a transmitting or receiving antenna (called reciprocity), differences arise in the path loss in each of the two directions due to terrain both close to the antennas and along the path between the antennas. This means if identical transmitters, receivers and antennas are used at each end, the antenna supporting structure height and terrain factors will cause the path loss from the central office station to the subscriber station to be different than the path loss from the subscriber station to the central office station.

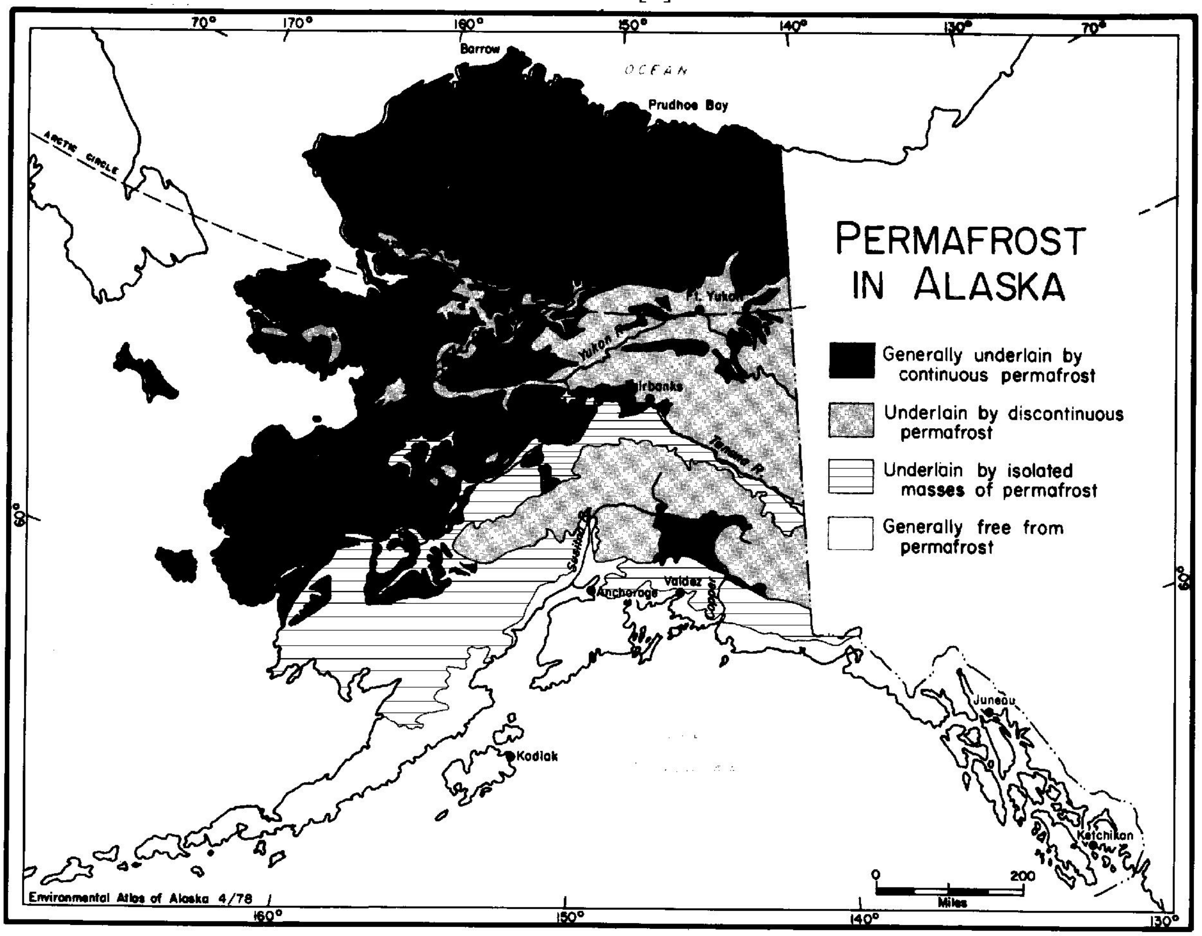
In some systems, the central office station transmitter is more powerful than the subscriber station transmitter, and the subscriber station antenna is lower in height than the central office station antenna. These two situations cause the received signal at the central office station to be worse than at the subscriber station. The path from the subscriber to the central office is sometimes called the "talkback" path or "up-link" path, and it is the one to which attention should be paid to determine system performance since it is the limiting path.

Treated wood utility poles, guyed lattice towers and self-supporting lattice towers are most frequently used to support BETRS system antennas at the central office. A 30 ft, class 5, treated wood pole or existing building structure normally is used at the subscriber. Wood poles normally are set 5 to 8 ft in native soil giving a height above ground of 22 to 25 ft. To reduce frost jacking (also called heaving), the buried part of the pole should be wrapped in visqueen to reduce the adfreeze bonding strength of the soil. Fig. 22 shows the locations of permafrost in Alaska.

Adfreeze bonding is the frozen bond between the water in the soil and the pole, which develops as the soil freezes in the winter. If the soil is very moist, it expands by nearly 10% of the volume of the moisture contained in the soil. As winter progresses, the area over which the adfreeze bond is gripping the pole becomes large enough to be stronger than the forces holding the pole in the ground (its weight and the friction of the unfrozen soil packed around it). At this time the pole will start to rise with the freezing soil as the soil expands. As the pole is drawn out of the hole, the walls of the hole often collapse inward. The following spring, thawing begins at the surface and, as it progresses down, the soil at the top has time to reconsolidate around the pole. This, plus the collapsed soil in the hole, hold the pole in the heaved position. Visqueen provides a low friction surface between the frozen soil and the pole thus preventing heaving.

For self-supporting towers, concrete foundations are the most feasible in rural Alaska. A basic design requirement is the foundation weight must exceed the expected tipping reaction from wind loads. In areas with poor soil strength, a large pad with a central slug is required to counteract the tipping moment. Appendix D provides example antenna supporting structure foundations for poor soils. Generally, it is a good idea to use foundations designed by civil engineers familiar with the area.

Fig. 22
Permafrost in Alaska
Source: [7]



Most tower manufacturers build their products according to Electronic Industries Association standard EIA-222-E.[53] This specification also includes useful applications information. From a structural point of view, the most important factors are wind and ice loading.

Wind close to the ground is slowed by surface roughness, especially trees and tall, heavy brush. Wind speed increases with height above ground as determined by the wind gradient. The upper part of an antenna supporting structure is subjected to higher wind loads. This load is transmitted through the structure to the foundation and foundation attachments. The following expression gives the relationship between the wind speed v(h) at any height h and the speed $v(h_0)$ at some reference height h_0:

$$v(h) \approx v(h_0)\left(\frac{h}{h_0}\right)^{1/\alpha} \qquad (62)$$

where α is the wind gradient factor, which depends on the surface roughness and whether the average or peak winds are being considered. Eq. (62) can be used to find the ratio of the surface wind speed v_0

(at a standard height h_0 = 33 ft) to gradient speed v_g at height h_g. The height h_g is the height at which the ground friction has negligible effect on the wind speed:

$$\frac{v_s}{v_g} \approx \left(\frac{h_0}{h_g}\right)^{1/\alpha} \qquad (63)$$

Table 6 summarizes some measured values of α, h_g, and v_s/v_g for various types of ground surfaces.

Table 6
Wind Gradients
Source: [14]

Surface Roughness	α	h_g (ft)	v_s/v_g
Flat, open country	7	900	0.62
Wooded areas, towns	3.5	1,300	0.35
Large cities	2.5	1,700	0.21

Wind speeds continually fluctuate. Speeds exhibit statistical distribution over time. Gust speeds, measured over short time periods (one second), are greater than speeds averaged over long time periods (one minute or hour). The following empirical expression gives the relationship between the speed v(t) averaged over time t and the speed $v(t_0)$ averaged over a one hour period t_0:[14]

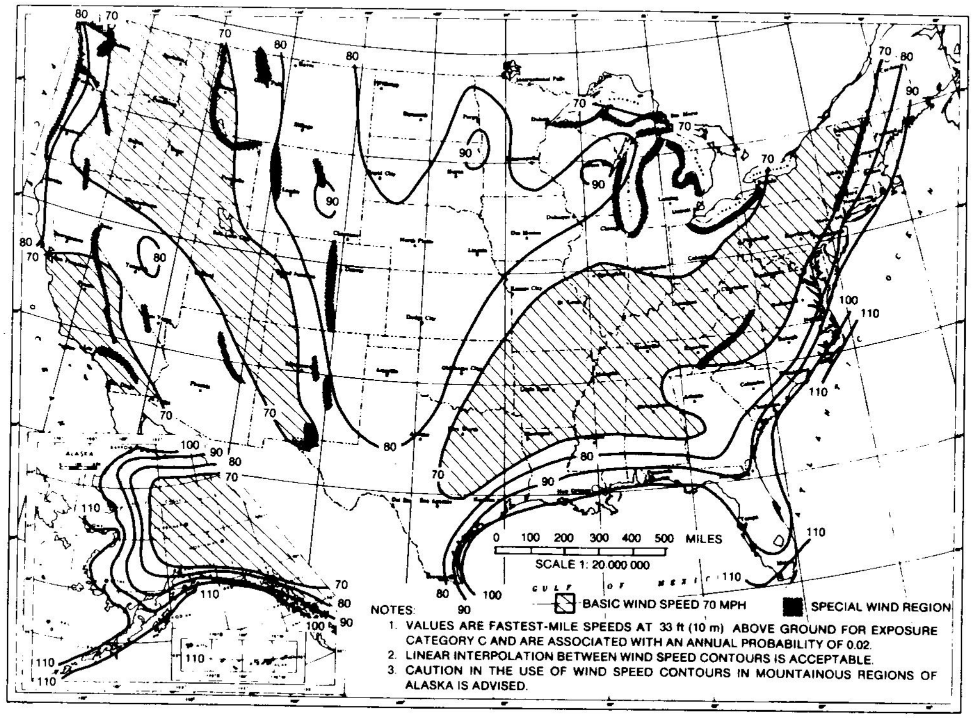
$$v(t) = v(t_0)\left[1 + k_0 \log\left(\frac{t_0}{t}\right)\right] \qquad (64)$$

where k_0 = 0.158.

Antenna supporting structures designed only for average wind speeds will fail under gust loads. Therefore, gust factors should be used in structure specifications. Most structures used in BETRS applications are small enough to respond to one second gusts. It is standard practice to use a 30% gust factor, which means the gust speed is 1.3 times the average speed. While this gust factor is usable in many situations, mountainous regions along the coastal areas of Alaska are known to have extreme winds; in particular, the Aleutian Islands and certain parts of southeastern Alaska have particularly high wind speeds.

Fig. 23 shows the wind speeds expected to occur in Alaska in a 50 year period. This illustration is very broad and does not indicate the peculiarities of specific areas (for example, mountainous regions) where winds may be much greater than shown.

Fig. 23
Basic Wind Speeds (miles per hour)
Source: Fig. 250-2, [52]



In some system design calculations and when using FCC and CCIR graphic aids, it may be necessary to convert from the field strength at an antenna location to the power and voltage levels at the antenna terminals. Field strength is the electric potential gradient per meter in the direction of the electric field vector at the location and usually is given in μv/m. The field strength does not depend on the antenna type, whereas the actual power delivered through the antenna to the antenna terminals does depends on the antenna. In the following, quantities enclosed in square brackets [ ] are dB values.

The conversion between field strength and power is readily made. For a given field strength E and wavelength λ, the power delivered through an isotropic antenna is given by

$$P_i = \frac{\lambda^2 E^2}{480\pi^2} \qquad (65)$$

In the above expression, if E is given in v/m and λ in m, the derived power P_i is in watts. If the field strength is given in dBμv/m, the power received through an isotropic antenna, in dBm, may be found from

$$P_i(dBm) = [E] + 20\log\lambda - 126.76 \qquad (66)$$

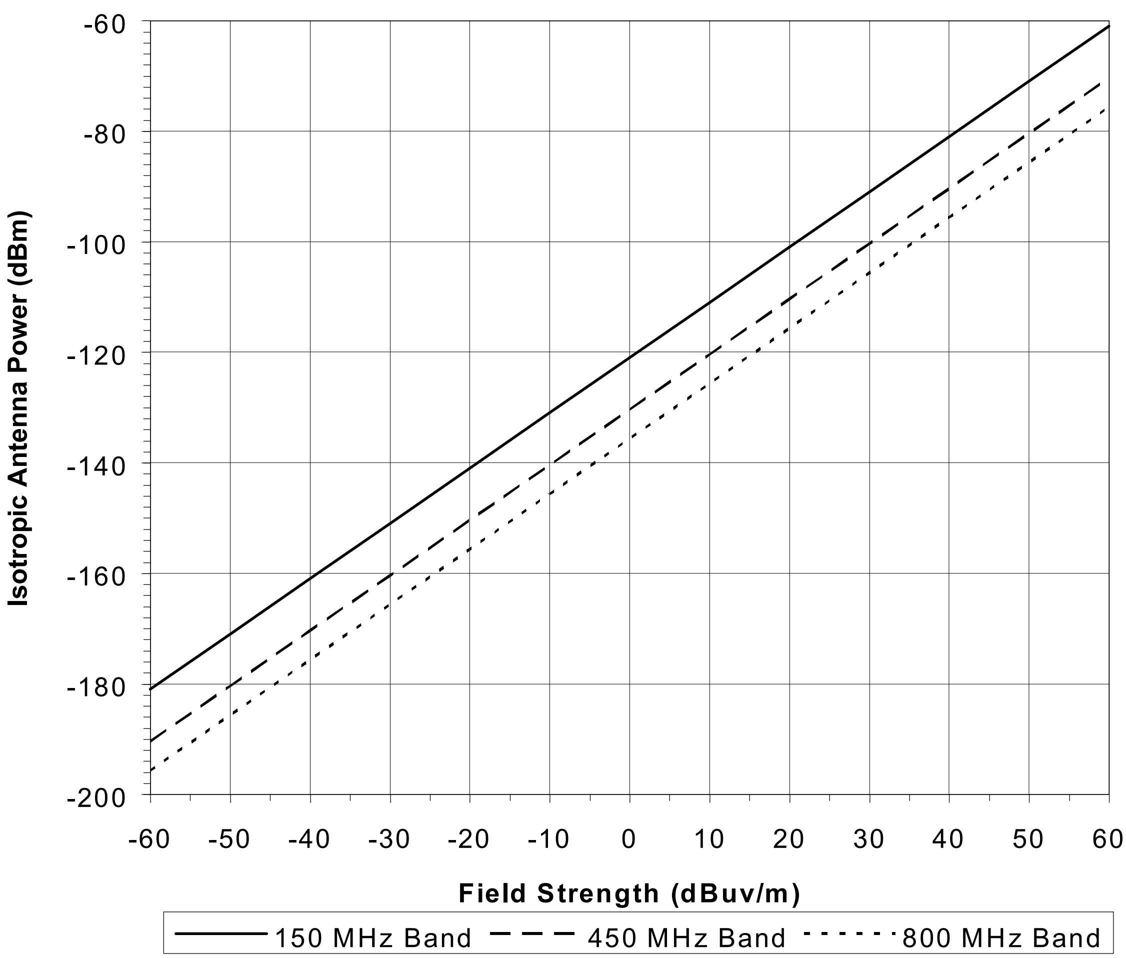
where

$[E]$ = field strength in dBμv/m and λ = wavelength in m. If the field strength is given in μv/m, it may be converted to dBμv/m by

$$[E] = 20\log E(\mu v / m) \tag{67}$$

Fig. 24 may be used to quickly convert between the power through an isotropic antenna and the field strength at the antenna location.

Fig. 24
Converting Between Field Strength and Isotropic Antenna Power



The voltage, in dBμv, at the terminals of a half-wave dipole antenna is given by

$$\left[\left[V_{dp}\right] = [E] + 20\log\lambda + 20\log\frac{1}{\pi}\right] \tag{68}$$

If the voltage is given in μv, it may be converted to dBμv by

$$\left[V_{dp}\right] = 20\log V_{dp}\,(\mu v) \tag{69}$$

The voltage at the terminals of an antenna having gain G_d with respect to a half-wave dipole is given by

$$\left[V_r\right] = [E] + \left[G_d\right] + 20\log\lambda - 9.94 \tag{70}$$

where the constant $-9.94 = 20\log\frac{1}{\pi}$.

15. Coaxial Cables and Connectors

Coaxial cables and connectors with 50 ohm characteristic impedance are used in BETRS systems. It is very important to use high quality cable and connectors and to waterproof all outdoor connections. Common cable constructions use a solid polyethylene dielectric or a foam core dielectric. Air dielectric cables should be avoided because of the need for dry air pressurization. Common cables use a single or double braided, untinned or tinned copper shield or a semi-rigid corrugated tubing or tape type shield (commonly called "hardline" and semi-flexible). Semi-rigid cables are preferred over the braided shield cables because the former have technically superior performance (but are more expensive).

Coaxial cables are transmission lines that must be matched to the loads at each end. Under matched load conditions, the loss in coaxial cables is directly proportional to the cable length. Unmatched loads lead to reflection losses. For example, if the cable has 2 dB attenuation at the operating frequency, but the VSWR at the load is 4:1, the actual transmission line loss is closer to 3.3 dB (2 dB line loss plus approximately 1.3 dB reflection loss). The output impedance of radio equipment is closely matched to 50 ohms; however, the impedance of even high quality antennas varies somewhat with frequency. A VSWR no worse than 1.5:1 generally is required for antennas over the band used. This VSWR results in, at most, 0.1 dB additional loss for typical situations.

In general, the larger the coaxial cable diameter, the less its attenuation at any given frequency. For short runs (< 10 ft) RG-58C/U, which is a small cable, is acceptable in the 150 and 450 MHz bands but should not be used at all in the 800 MHz band. For runs up to 50 ft, RG-213/U (single braided shield; formerly RG-8/U) or RG-214/U (double braided shield) is acceptable in the 150 and 450 MHz bands but should be avoided in the 800 MHz band.[22] For longer lengths in the 150 and 450 MHz bands, and at any length in the 800 MHz band, semi-rigid cables should be used exclusively.[23] Attenuation per 100 ft of length for various coaxial cables at the midband frequency in each BETRS band is given in Table 7. This table also shows the minimum bend radius for each cable type, which is 10X the cable outside diameter. The user must be careful to differentiate between true mil-spec RG213/214 and commercial versions. Commercial versions of these cable types have almost twice the attenuation at BETRS frequencies.

When choosing a coaxial cable for BETRS applications, the primary considerations are attenuation and outdoor performance. The maximum attenuation to be used for the coaxial cable run will be based on the available transmitter power, link margins and what is economically achievable. For most systems, 1 or 2 dB maximum attenuation should be used as a target. These attenuations represent a power loss factor of 79% and 63%, respectively. For example, if the transmitter output power is 2 watts, the power delivered to the antenna through a line with 2 dB loss will be (0.63 X 2 watts =) 1.26 watts.

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[22] The "RG" nomenclature has its origin with the military and means the “Radio Guide” specification under which cables were specified. RG-8/U is no longer covered by military specifications, but it still is widely available from commercial cable manufacturers.

[23] The most commonplace semi-rigid cables are made by Andrews Corp. and Celwave, although there are several other manufacturers of these types of cables in the US including Times Microwave Systems and Radio Frequency Systems. All manufacturers make a variety of connectors that match the cable. Andrews also provides a free DOS software program (called I-L-CALC) to simplify the attenuation and insertion loss calculations for any frequency and length and SC-CALC, which compares small cable sizes (up to ½” semi-rigid foam).

With long runs, a 3 dB attenuation may be acceptable, but the power delivered to the antenna will be half of that available at the transmitter connector (0.50 power loss factor).

Since it is difficult to completely seal any outdoor cable run from moisture absorption, cables and connectors specifically designed for all-weather use must be installed. Also, the outer jacket of the coaxial cable used in outdoor applications must not deteriorate under long-term exposure to the sun and must not become brittle at low temperatures (at least -40°C).

In BETRS applications, the most common connector types are N, BNC and UHF (also called PL-259).[24] The N connector is preferred and is used in all frequency bands. The UHF and BNC connectors are seldom used in the 450 and 800 MHz band. If the UHF (PL-259) connector is required in order to match the radio or antenna connector, use a connector with a silver-plated body and TEFLON® dielectric.

Table 7
Coaxial Cable Attenuation At BETRS Frequencies

Cable Type	*Attenuation (dB/100ft.)*			10X Bend Radius	OD (inches)
	155 MHz	457 MHz	841 MHz		
RG-58C/U	6.3	11.9	17.7	> 2.5 in.	0.25
RG-213/U (RG-8/U)	2.8	5.0	7.7	> 4.5 in.	0.405
3/8 in. foam semi-rigid	1.32	2.32	3.21	> 4.5 in.	0.44
1/2 in. foam semi-rigid	0.86	1.52	2.13	> 6.5 in.	0.63
7/8 in. foam semi-rigid	0.47	0.84	1.18	> 11 in.	1.09
1 1/4 in. foam semi-rigid	0.35	0.62	0.87	> 16 in.	1.55
1 5/8 in. foam semi-rigid	0.28	0.52	0.74	> 20 in.	1.98

Only high quality weatherproof connectors should be used. Generally, the higher the cost, the higher the quality. Connectors can be purchased in MIL-SPEC or "commercial" grades. Commercial grade connectors are about 1/3 to 1/2 the cost of MIL-SPEC connectors, but they are low quality and should be avoided. MIL-SPEC connectors are specified in the MIL-C-39012 series documents.[25] Crimp type connectors (both center pin and cable body) are the best, but a special crimping tool is required. Use only connectors with gold-plated center pins. Connector bodies should be silver or nickel plated annealed brass (silver plated is better). TEFLON® dielectrics are the best.

Many companies offer cable/connector assemblies. Unfortunately, the quality of these assemblies, especially the ones with braided shield coaxial cable, varies considerably among different manufacturers. The investment in a good quality crimping tool (several hundred dollars) and practice with it will provide more consistent connections and save many trips to the field for cable repair. Poor connector assembly and poor weather protection can cause degraded or interrupted link performance. In such cases, a measurement of VSWR at the radio may not indicate a problem because the high loss masks the high VSWR at the antenna. Thus, VSWR measurements are more meaningful when taken at the antenna. This aspect of field testing is covered in greater detail later.

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[24] Some trunked radio systems use the SMA connector on handheld radios and for internal connectors within the radio equipment.

[25] Some manufacturers of MIL-SPEC connectors are AMP, Kings Electronics Co., MA/COM and ITT

A properly installed pair of connectors (one at each end) will add no more than 0.1 dB of loss to the cable. All outdoor RF connections should be sealed with a cold-shrink tubing, heat-shrink tubing or wrapped with a rubber insulating tape and sealed with a vinyl tape and an electrical coating such as 3M™ Scotchkote®. The rubber insulating tape used for sealing underwater electrical connections at submersible well pumps works well, but these rubber compounds must be covered with an ultraviolet resistant vinyl tape. All outer layer taping should be done with 100% coverage, 1/2 to 1/3 overlap, in at least two layers. The electrical coating should extend at least 1 in. beyond the tape. Some cable manufacturers have sealing products specifically made for outdoor applications.[26] However, almost all cold-shrink and heat-shrink materials are degraded by ultraviolet radiation from the sun and, therefore, should be wrapped with a low temperature black vinyl tape such as 3M™ Super 88. The tape should be sealed with an electrical coating to keep it from unraveling.

Coaxial cables must be supported on the tower or antenna supporting structure. There should be no tension or strain on the connectors. A short service loop will eliminate strain, but care should be taken not to bend the cable too sharply (see Table 7). The cable should be attached to the tower with clamps made for the purpose (see any cable or antenna manufacturer's catalog). Clamps should be spaced at 3 or 4 ft intervals. Vinyl tape should not be used in place of clamps.

[26] Some heat-shrink products are Panduit HSTT series thinwall and HST series thickwall. The 3M™ Cold Shrink™ Weatherproofing Kit is a comparable cold-shrink product.

16. Grounding and Protection

Grounding and protection is required for personnel safety and equipment protection. Alaska is not considered a high-lightning state; nevertheless, interior Alaska has frequent summer lightning storms and there is sufficient probability of lightning storms in most other areas of the state during the summer to require attention be paid to lightning protection.

Dry winter storms or winds can cause large build-ups of static electricity on isolated metallic structures, and this must be drained to a common grounding point. Frozen ground is an insulator and earth grounding is non-existent during the winter in many areas. Nevertheless, proper bonding of all equipment provides for safety and prevents static build-up on isolated metal objects.

Article 810 of the NEC specifies the grounding requirements for radio systems installed on subscriber premises. It requires all masts and metal antenna supporting structures to be grounded. The radiating elements of most BETRS antennas have dc continuity to the mount, which must be bonded to ground. If the antenna is supported by a grounded metallic structure, the antenna can be bonded directly to the structure, or a separate lead directly to ground can be used. Article 810 refers to Article 250 for specific grounding electrode details.

In the case of hardline, the coaxial cable feeding the antenna should be bonded to ground at two points using a grounding kit from the cable manufacturer. The bonds should be made near the connection at the antenna and near the point of entry into the building. Although the NEC allows the bonding conductors to be as small as #10 AWG copper, a minimum #6 AWG copper conductor should be used for added mechanical strength (the larger, the better). Ground leads should be as straight as possible with no sharp bends. Bonding cannot be done reliably with braided shield coaxial cable as no kits are available. In the case of braided shield cable, the shields will be bonded through the connectors at each end; therefore, it is very important the antenna and radio equipment be properly grounded.

All indoor radio equipment must be grounded. All equipment, including outdoor supporting structures, must be bonded together, preferably at one point. If a grounding electrode does not exist, one must be provided (generally an 8 ft ground rod or copper plate having 2 sq ft of area).[27] If one does exist, the equipment must be bonded to it. Where separate grounding electrodes are used for power and radio, they must be bonded together using a #6 or larger copper conductor. All connections should be made with irreversible compression connectors or exothermic connections; split-bolts should be avoided because they loosen over time from thermal cycling.

Antenna discharge units (coaxial protectors) are not required by the NEC where the coaxial cable shields are properly grounded. However, in areas of high lightning activity, these devices will improve the safety and reliability of the BETRS system if installed and grounded properly.

Perhaps the best practical guide to bonding and grounding of antenna supporting structures is given in Appendix B of REA Telecommunications Engineering & Construction Manual, Section 810, *Electrical Protection of Electronic Analog and Digital Central Office Equipment*.[44] A copy of this portion of the REA practice is provided in Appendix I. Sources of radio frequency equipment grounding products and information are [56] and [1]. A typical installation is shown in Fig. 25.

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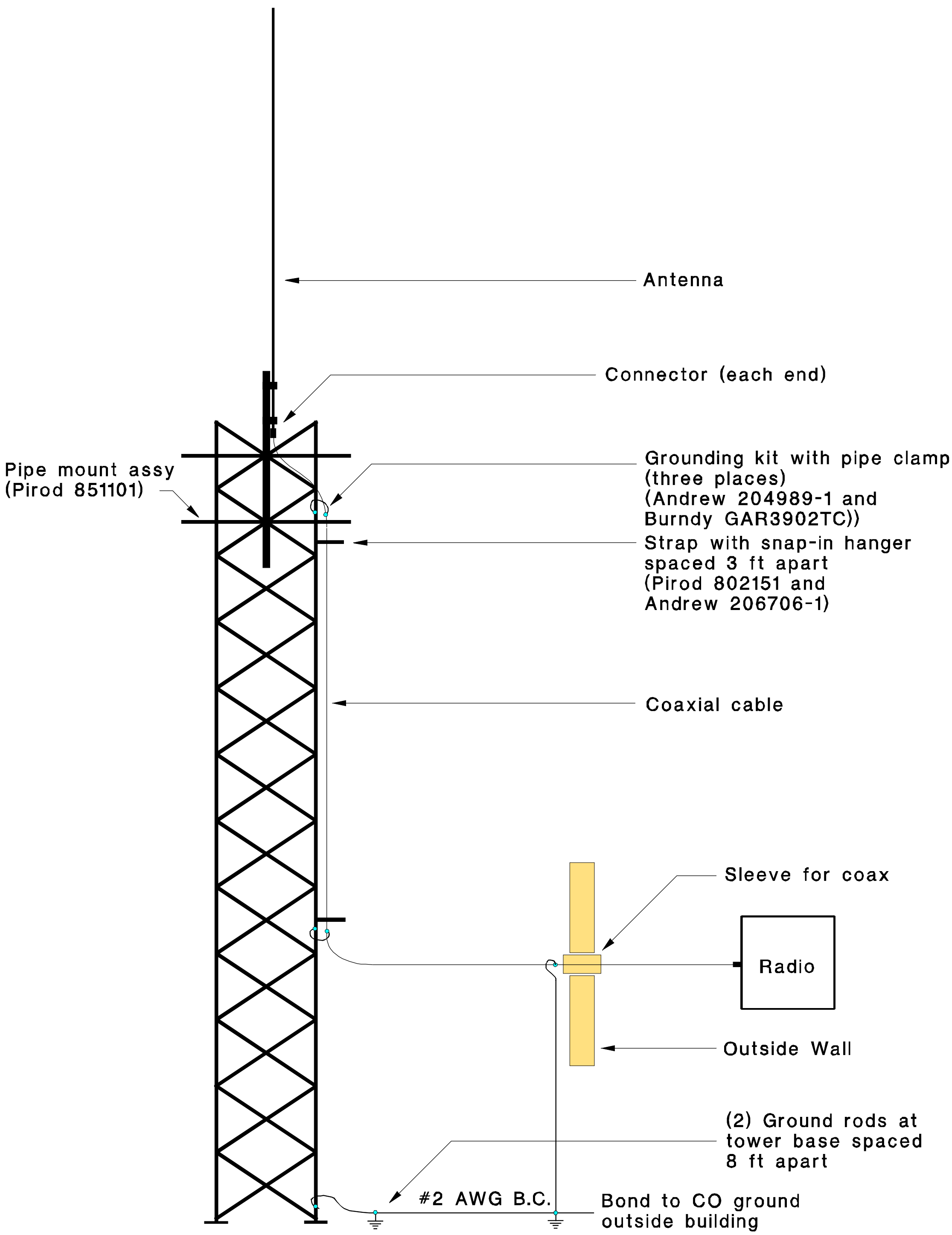
[27] See NEC § 810-21 and § 250-81.[51]

Fig. 25
Typical Antenna Installation Grounding



17. Quality of Service

Quality of service is a subjective measure, usually based on the opinions of many people. The objective of any telecommunications system is to provide a high opinion score on a very large majority of connections. The design of telecommunication systems recognizes that a small but measurable number of connections will have lower, possibly even unacceptable, quality.

It is the goal of BETRS link design to provide service equivalent to that provided by a landline as discussed below. This requires a high SNR (at least 30 dB) with sufficient fade margin to counteract multipath fading 90% of the time. In many situations, this is not possible. Nevertheless, the typical subscriber will be very happy to have the BETRS system when it is first installed even if the link is marginal.

The initial attitude by a user is "degraded service is better than no service." However, as time goes on and the BETRS is used more and more, marginal service may become unacceptable to the subscriber. At first glance, it would appear more transmitter power can solve low signal level problems. However, higher transmitter power normally is not feasible in systems already installed. Better and higher antennas usually provide improved performance at lower cost than higher transmitter power. In many cases, the only remedy to marginal signal level (and associated poor service quality) is a repeater.

The quality of a landline subscriber loop is based on the transmission performance criteria summarized in Table 8.

Table 8
Landline Subscriber Loop Performance Requirements

Quality	Circuit Noise (dBrnC)	Circuit Noise (dB3kHz)	Power Influence (dBrnC)	Circuit Balance (dB)	Circuit Loss (dB)
Acceptable	≤ 20	≤ 40	≤ 80		≤ 8
Marginal	20 to 30	40 to 60	80 to 90	50 ~ 60	8 to 10
Unacceptable	> 30	> 60	> 90	< 50	> 10

The power influence and balance requirements normally are irrelevant to radio systems unless the radio terminals are connected to outside plant cable. In most situations, the terminals will be installed in the serving central office and on the subscriber's premises, and outside plant cable is not used.

The loss requirement usually is met by default because of the limited loop length between the radio terminal and the subscriber's telephone. A typical BETRS installation will provide an insertion loss of 3 dB at 1 kHz, which is optimal in terms of subscriber satisfaction.[18]

This leaves the circuit noise requirements as the only variables in the quality of service question. As discussed above and elsewhere in this monograph, all BETRS links are subject to unavoidable fading. The performance goals should recognize this. The following suggestions are made:

- A link should have acceptable circuit noise (both C-message and 3 kHz flat) at least 50% of the time, and
- A link should have 20 dB of quieting at least 90% of the time.

The 3 kHz flat requirements are less stringent than the C-message requirements because the noise bandwidth measured through the 3 kHz flat filter is wider. The 3 kHz flat filter does not appreciably attenuate the 60 Hz fundamental powerline frequency or its first few harmonics like the C-message filter. Because the connection between the radio terminal and the subscriber's telephone set is short it should not be influenced by longitudinal powerline currents. Therefore, measurements with a 3 kHz flat filter should be well within the requirements given above. Any excursions above the limits indicate a problem in the subscriber's ac power supply or grounding. This can be determined by operating the subscriber station on its own battery and without any connection to the ac power source. If the noise measurement improves significantly, grounding and bonding at the site should be improved or a powerline noise conditioner or filter should be used.

Radio frequency and other tests and requirements are discussed in the Tests and Measurements section.

18. Traffic Considerations

This section primarily is concerned with determining the number of radio channels necessary to serve a number of subscribers with a point-to-multipoint, or trunked, system. In trunked systems, a number of radio channels are shared by a greater number of subscribers on a traffic demand basis. Point-to-point systems generally serve only one subscriber, although some systems allow partyline operation in which a number of subscriber units share a common frequency pair. Such systems are not discussed in this section.

The FCC rules are based on objective need for frequency spectrum.[28] Further, the FCC requires a tradeoff between intensity of use (traffic load) by different public mobile radio users - such as pagers, two-way mobile and rural radio - and quality of service. The FCC's objective need standards were not designed with telephony traffic in mind, and any trunked BETRS system equipped according to FCC requirements almost always will be under trunked. This section will not argue the merits or demerits of the FCC's requirements but, instead, will describe the basic traffic engineering methods that result in properly equipped BETRS systems.[29]

Presently, there are only two multipoint radio systems designed specifically for BETRS applications, one a digital system and the other an analog FM system. Both systems use proprietary signaling protocols. A few other systems have been adapted for BETRS. One is an IMTS (Improved Mobile Telephone Service) system, which is based on a largely outmoded signaling protocol, and the other is an LTR® system, which is based on a signaling protocol designed by E.F. Johnson Company.

All multipoint systems allow a subscriber station to choose among at least two radio channels on a trunking basis. Each channel, or trunk, consists of two frequencies for full-duplex operation. Generally, one channel is used for call setup and signaling between the central office and subscriber stations. Some systems do not make the signaling channel available to traffic while others do. For example, a system equipped with six radio channels may only have five of those channels available to traffic. From a traffic engineering standpoint, this is an important point because a system with six traffic channels can carry considerably more traffic than a system with five.

The Poisson, Erlang B, Binomial Distribution and Engset Distribution are the most commonly used traffic formulas in telephony systems. The remainder of this section is devoted to the application of these traffic formulas. The Poisson and Erlang B formulas both assume an infinite number of traffic sources (subscribers), whereas the Binomial and Engset formulas assume finite traffic sources. In BETRS systems, where the number of sources is far from infinite, the Erlang B and Poisson formulas cannot be accurately applied. Therefore, it is usual practice to use the Binomial and Engset Distributions in their place, respectively.

Table 9 summarizes the basic characteristics of the most common traffic formulas and Table 10 summarizes the formulas themselves. Table 9 also indicates if the formula is normally

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[28] FCC rules Part 22, par. 22.16.

[29] It is necessary to obtain a waiver of the FCC's objective need standard to properly equip a BETRS system.

applied in BETRS applications. Even though the Poisson, Erlang B and Erlang C formulas normally are not used in BETRS applications, they are included for comparison with the Binomial and Engset Distributions.

Table 9
Traffic Formula Characteristics

Traffic Formula	Blocked Calls	No. of Traffic Sources	BETRS Application	Remarks
Poisson	Held	Infinite	No	
Erlang B	Cleared	Infinite	No	
Erlang C	Delayed	Infinite	No⊗	
Binomial Distribution	Held	Finite	Yes	Used in place of Poisson
Engset Distribution	Cleared	Finite	Yes	Used in place of Erlang B

⊗ The FCC rules historically specify the Erlang C delay table, but it cannot be accurately applied to trunked telephony traffic.

Table 10
Traffic Formula Summary

Formula	Blocking Probability
Poisson	$P = 1 - e^{-A}\sum_{I=0}^{T-1}\frac{A}{i!}$
Erlang B	$P = \frac{A^T/T!}{\sum_{i=0}^{T}\frac{A^i}{i!}}$
Erlang C	$P = \frac{A^T T/[T!(T-1)]}{\sum_{i=0}^{T-1}\left(\frac{A^i}{i!}\right) + \frac{A^T T}{T!(T-1)}}$
Binomial Distribution	$P = \sum_{i=T}^{S-1}\frac{(S-1)!}{i!(S-1-i)!}a^i(1-a)^{(S-1-i)}$
Engset Distribution	$P \approx \frac{\frac{(S-1)!}{T!(S-1-T)!}\left(\frac{A}{S-A}\right)^T}{\sum_{i=0}^{T}\frac{(S-1)!}{i!(S-1-i)!}\left(\frac{A}{S-A}\right)^i}$

where

P = Blocking probability
A = Total offered traffic in Erlangs (Note: 1 Erlang = 36 CCS)
T = Number of trunks
S = Number of subscribers
a = Average offered traffic in Erlangs per subscriber (Note: A = Sa)
i = index

Ideally, the traffic load is based on subscriber traffic measurements in the exchange area where the BETRS systems is being deployed. Such measurements establish a starting point for determining the number of radio channels. Because of the small number of channels normally involved and the fact that it takes only a few subscribers with above average call activity to introduce excessive blocking, some adjustments to the measurements may be required for a particular system.

Where traffic measurements are not available, the following information can be used to establish a starting point: Regular POTS subscribers use the telephone infrequently compared to business subscribers. This translates into different traffic load per subscriber. Traffic studies in rural Alaska have shown a range of 0.056 to 0.111 Erlang (2 to 4 CCS) originating plus terminating traffic per subscriber line. The lower end primarily applies to residential subscribers and the upper end primarily applies to business subscribers. When the number of calls during the busy hour is known based on a peg count study, the total offered traffic is given by

$$A = C\,T_c \text{ Erlangs} \qquad (71)$$

where A = Total traffic during the busy hour, C = number of calls during the busy hour and T_c = average call holding time in hours. The average holding time is approximately 300 seconds (0.05 hours) for all calls, but this can easily vary by 25% for any given exchange. The total traffic A from equation (71) can be divided by the total number of subscribers S to determine the average traffic per subscribers,

$$a = A\,/\,S \text{ Erlang per subscriber} \qquad (72)$$

where a = average unit traffic load in Erlangs per subscriber.

As a design aid, Tables 11 and 12 give the number of subscribers that may be served by up to eight radio channels with a 1% and 2% blocking probability, respectively, and at various unit traffic loads using the Binomial Distribution formula. Tables 13 and 14 give the same information using the Engset Distribution formula. The 2% blocking is the maximum allowed in Alaska for line-to-trunk matching.[30]

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[30] The allowable blocking is regulated by the Alaska Public Utilities Commission; see 3 AAC 52.310(d).

Table 11
Binomial Distribution, 1% Blocking Probability

1% Blocking	Number of Subscribers Served By T Radio Channels							
Unit Traffic Load - Erlangs/Subscriber (CCS/Subscriber)	**T = 1**	**T = 2**	**T = 3**	**T = 4**	**T = 5**	**T = 6**	**T = 7**	**T = 8**
0.028 (1.0)	1	7	17	32	49	67	87	107
0.042 (1.5)	1	5	12	22	33	46	59	73
0.056 (2.0)	1	4	9	17	25	35	45	55
0.069 (2.5)	1	3	8	14	21	29	37	45
0.083 (3.0)	1	3	7	12	18	24	31	38
0.097 (3.5)	1	3	6	10	15	21	27	33
0.111 (4.0)	1	2	5	9	14	19	24	29
0.125 (4.5)	1	2	5	8	12	17	21	26
0.139 (5.0)	1	2	5	8	11	15	20	24
0.153 (5.5)	1	2	4	7	11	14	18	22
0.167 (6.0)	1	2	4	7	10	13	17	20

Table 12
Binomial Distribution, 2% Blocking Probability

2% Blocking	Number of Subscribers Served By T Radio Channels							
Unit Traffic Load - Erlangs/Subscriber (CCS/Subscriber)	**T = 1**	**T = 2**	**T = 3**	**T =4**	**T = 5**	**T = 6**	**T = 7**	**T = 8**
0.028 (1.0)	1	9	22	38	57	77	99	121
0.042 (1.5)	1	6	15	26	39	52	67	82
0.056 (2.0)	1	5	12	20	29	40	51	62
0.069 (2.5)	1	4	10	16	24	33	41	51
0.083 (3.0)	1	4	8	14	20	27	35	43
0.097 (3.5)	1	3	7	12	18	24	30	37
0.111 (4.0)	1	3	6	11	16	21	27	32
0.125 (4.5)	1	3	6	10	14	19	24	29
0.139 (5.0)	1	3	5	9	13	17	22	26
0.153 (5.5)	1	2	5	8	12	16	20	24
0.167 (6.0)	1	2	5	8	11	15	19	22

Table 13
Engset Distribution, 1% Blocking Probability

1% Blocking	Number of Subscribers Served By T Radio Channels							
Unit Traffic Load - Erlangs/Subscriber (CCS/Subscriber)	**T = 1**	**T = 2**	**T = 3**	**T = 4**	**T = 5**	**T = 6**	**T = 7**	**T = 8**
0.028 (1.0)	1	7	18	33	51	72	92	116
0.042 (1.5)	1	5	12	23	35	48	62	78
0.056 (2.0)	1	4	10	17	27	37	48	59
0.069 (2.5)	1	3	8	14	22	30	39	48
0.083 (3.0)	1	3	7	12	18	25	33	41
0.097 (3.5)	1	3	6	11	16	22	28	35
0.111 (4.0)	1	2	6	10	14	19	25	31
0.125 (4.5)	1	2	5	9	13	18	22	28
0.139 (5.0)	1	2	5	8	12	16	20	25
0.153 (5.5)	1	2	4	7	11	15	19	23
0.167 (6.0)	1	2	4	7	10	14	17	21

Table 14
Engset Distribution, 2% Blocking Probability

2% Blocking	Number of Subscribers Served By T Radio Channels							
Unit Traffic Load - Erlangs/Subscriber (CCS/Subscriber)	**T = 1**	**T = 2**	**T = 3**	**T = 4**	**T = 5**	**T = 6**	**T = 7**	**T = 8**
0.028 (1.0)	1	9	23	41	61	84	108	132
0.042 (1.5)	1	6	16	28	41	56	72	89
0.056 (2.0)	1	5	12	21	31	43	55	67
0.069 (2.5)	1	4	10	17	26	35	45	55
0.083 (3.0)	1	4	9	15	22	29	37	46
0.097 (3.5)	1	3	7	13	19	25	32	40
0.111 (4.0)	1	3	7	11	17	22	28	35
0.125 (4.5)	1	3	6	10	15	20	26	31
0.139 (5.0)	1	3	6	9	14	18	23	28
0.153 (5.5)	1	2	5	9	13	17	21	26
0.167 (6.0)	1	2	5	8	12	15	20	24

19. Computerized Path Analysis

The path loss equations given in this guide can be coded in a spreadsheet or math computational program. However, if the model being used requires a path profile, it can take several hours to manually plot, and a coverage analysis of many paths is quite laborious. To speed up path analyses, there are a number of commercially available path analysis programs for PC compatible computers that considerably simplify the job.[31]

With these programs, the user normally can choose from a variety of path loss models and, depending on the program options or capabilities, run either an individual path or complete coverage analysis. Most programs are available with the USGS 3 arc-second terrain database for Alaska (and other parts of the US) on a CD-ROM.[32] It only is necessary to specify station parameters such as station coordinates, transmitter power, receiver sensitivity, frequency and antenna heights and a point-to-point path profile can be produced in a few minutes.

For point-to-multipoint applications, a full coverage analysis and plot of 360 radials from the central office station can be performed in a few hours instead of days or weeks. Coverage is based on signal level contours surrounding the central office station. Generally, one contour is determined at the lowest signal level for reliable operation. This level depends on the receiver sensitivity, the accuracy of the terrain database or map, and an estimate of the received signal level variability and the fade margin required. When a particular subscriber is located in the coverage area, a separate point-to-point study should be made to confirm the coverage predictions.

For most analog FM BETRS systems, the suggested lowest received signal level contour is –100 dBm. This gives about 16 dB margin over FM receiver threshold (operation right at the threshold will be unacceptable by almost any subscriber, especially over any time period). For digital systems, the lowest received signal contour may be about 10 dB higher but will depend on the system.

The path loss model and assumptions determine where this contour lies. The actual median received level at any given place can differ from the computed contour level by 10 to 20 dB. This is why computer or manual analysis can never substitute for actual on-site tests. Nevertheless, the computer or manual exercises help predict coverage and are useful tools in radio engineering.

When preparing point-to-point analyses using the US Geological Survey (USGS) digitized database, at least one limitation must be observed. USGS developed the database for Alaska from 1:250,000 scale maps using the WGS-72 datum. The width of a pencil line is about 1/4 mi on such a map. If a mountain peak or hilltop lies between two sampling points, it will not appear in the database. Therefore, elevation errors can be significant enough to show a line-of-

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[31] See Appendix G for a list of vendors.

[32] Some implementations of path analysis software that use the USGS database allow the input coordinates to be based on either NAD-27 or WGS-72 datum. Caution is required when inputting NAD-27 coordinates for Alaska locations because of faulty datum conversion code in at least one program (EDX Engineering). See Appendix F.

sight path where none really exists. This limitation can be overcome by double-checking all point-to-point paths on 1:63.360 scale maps (or higher scale maps if available) to identify all peaks.[33] Most path analysis programs allow the computerized profile plot to be edited with the more accurate data.

Most programs have the ability to select from several propagation models. Each model will give different results on a given path. Therefore, it is important to understand the strengths and weaknesses of the models to be used. To indicate the disparity between the results of different models consider two paths in northwestern Alaska. One, between Shungnak and Kobuk, is a line-of-sight path (which lacks full 1st Fresnel Zone clearance) shown in Fig. 26, and the other, between Kiana and Noorvik, is an obstructed path (with obstruction height of approximately 190 ft) shown in Fig. 27.

Table 15 summarizes the data associated with the two paths. Tables 16 and 17 provide a comparison of the different propagations models available in a program called RPATH by EDX Engineering, Inc. and the noted equations in this monograph.[34] The path losses are arranged in ascending order of difference Δ between the predicted loss and the free-space loss.

Some models do not apply to obstructed paths and they can be immediately rejected from the analyses of paths with diffraction characteristics (for example, FCC or CCIR alone, Okumura alone and free-space and ground-wave models alone).

It is apparent from Tables 16 and 17 that the FCC and CCIR models tend to overstate the loss on both line-of-sight and obstructed paths. The free-space model understates the loss, as would be expected, on both path types. The free-space model only applies when several Fresnel zone clearance is attained, which is not the case with the line-of-sight path in this example. The TIREM model seems to provide a reasonable loss value. Regardless of the path model used, field verification will prove or disprove whether any particular model is appropriate for the path in question.

The EDX Engineering RPATH propagation models are as follows:

<u>TIREM</u> - This model is based on propagation work by the National Bureau of Standards and others. TIREM stands for Terrain Integrated Rough Earth Model. It takes into account ground wave losses including diffraction effects. This is a complete and complex model.
<u>Free Space + RMD</u> - This model is equivalent to the ground-wave loss equations presented in this monograph. RMD stands for Reflection plus Multiple Diffraction.
<u>FCC + RMD</u> - This model is based on propagation curves published by the FCC with adjustments for ground-wave losses including diffraction effects. The FCC curves do not specifically account for diffraction effects so these are added in when necessary.
<u>CCIR + RMD</u> - The CCIR curves are similar to those published by the FCC. This model provides adjustments for ground-wave losses including diffraction effects.

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[33] USGS now has 1:25,000 scale maps for many larger communities in Alaska.
[34] RPATH is only one of many path analysis programs available for the PC. See Appendix G for a comprehensive list.

Okumura - This model is based on the Okumura studies previously discussed in this monograph. As with the FCC and CCIR curves, the Okumura model does not specifically account for diffraction effects.

Okumura + RMD - This model is the same as above but has the additional adjustments for ground-waves and diffraction effects.

Table 15
Example Path Data

Parameter	Shungnak - Kobuk	Kiana - Noorvik
Type	Line-of-sight	Obstructed
Distance d	7.0 mi	19.3 mi
Frequency f	457 MHz	457 MHz
Wavelength λ	2.15 ft	2.15 ft
Antenna height h_t	50	50
Antenna height h_r	20	20
Diffraction parameter ν	0.2	✂1.7

Fig. 26
Shungnak to Kobuk Path

Fig. 27
Kiana to Noorvik Path

Table 16
Comparison of Propagation Models for the Shungnak to Kobuk Path (Line-of-sight)

Model or Equation	Predicted Path Loss	Δ	Remarks
A_{fs}	106.7 dB	0.0 dB	[Eq. (3)]
A_D	111.2 dB	4.5 dB	[Eq. (14)]
EDX RPATH Free Space + RMD	111.3 dB	4.6 dB	See text
EDX RPATH Okumura	118.1 dB	11.4 dB	See text
EDX RPATH TIREM	120.1 dB	13.4 dB	See text
A_{GS}	122.8 dB	16.1 dB	[Eq. (9)]
EDX RPATH Okumura + RMD	122.6 dB	15.9 dB	See text
EDX RPATH CCIR + RMD	138.3 dB	31.6 dB	See text
EDX RPATH FCC + RMD	142.8 dB	36.1 dB	See text

Table 17
Comparison of Propagation Models for the Kiana to Noorvik Path (Obstructed)

Model or Equation	Predicted Path Loss	Δ	Remarks
A_{fs}	115.5 dB	0.0 dB	[Eq. (3)]
A_D	133.5 dB	18.0 dB	[Eq. (14)]
EDX RPATH Free Space + RMD	133.7 dB	18.2 dB	See text
EDX RPATH TIREM	133.7 dB	18.2 dB	See text
EDX RPATH Okumura	135.0 dB	19.5 dB	See text
A_{GS}	140.3 dB	24.8 dB	[Eq. (9)]
EDX RPATH Okumura + RMD	153.3 dB	37.8 dB	See text
EDX RPATH CCIR + RMD	174.5 dB	59.0 dB	See text
EDX RPATH FCC + RMD	182.4 dB	66.9 dB	See text

In most computerized path analysis programs, the required input parameters are: [48]

- Frequency
- Great circle distance between the two radio terminal antennas
- Antenna heights
- Polarization
- Terrain characteristics
- Electrical constants of the earth
- Atmospheric refractivity at the surface

Frequency, distance, antenna heights and polarization were discussed in previous sections. The terrain characteristics required as input can take several forms. When a digitized terrain database is used, the program usually will develop the required information automatically. Some programs use a terrain irregularity factor Δh. For the Longley-Rice models Δh is defined as the interdecile range of terrain elevations; that is, the total range of elevations after the higher 10% and the lowest 10% have been removed. Table 18 shows suggested values for Δh absent more detailed information.

Table 18
Δh

Type of Terrain	Δh, m (ft.)
Flat (or smooth water)	0 (0)
Plains	30 (10)
Hills ("average" terrain)	90 (30)
Mountains	200 (60)
Rugged mountains	500 (150)

The electrical ground constants consist of relative permittivity (dielectric constant) and conductivity. It is not necessary to assign accurate values. Suggested values are given in Table 19.

Table 19
Electrical Ground Constants

Type	Relative Permittivity	Conductivity (Siemens/m)
Poor ground	4	0.001
"Average" ground	15	0.005
Good ground	25	0.020
Fresh water	81	0.010
Sea water	81	5.0

It should be noted that the only use to which electrical ground constants and polarization are put is to determine reflectivity of smooth portions of the ground where the incident radio waves are grazing or nearly so. At normal antenna heights, these parameters have little significance. If a value is required as input to a program, it is just as well to use "average" ground unless there is a compelling reason to do otherwise.

The surface reflectivity depends on many weather related factors. In Alaska, the minimum average value is 310 N-units but can vary from about 300 N-units in the Interior to 350 N-units over sea. Continental temperate corresponds to 320 N-units and maritime temperate corresponds to 350 N-units.

The surface refractivity generally, but not always, affects propagation paths greater than about 30 miles (50 km). The refractivity determines the earth radius factor, or K-factor, and the suggested values may be used as previously discussed.

20. Path Loss Data Entry Form

The form at the end of this section can be used to summarize path data. While it is intended primarily for point-to-point systems, it can be adapted for multipoint systems, as well.

Normally, a data entry form is filled out for each path, remembering a radio link has a path from the central office to the subscriber and another path from the subscriber to the central office. In many situations, both paths are identical, including transmitters, receivers, antennas and path losses. However, in some circumstances, the path loss may be different in each direction due to asymmetric diffraction losses or different transmitter output powers. The worse path determines the reliability of the link. The following explains each item:

Item 1 Site Name: Self-explanatory.

Item 2 North Latitude: Site A and Site B latitude; taken from a USGS topographic map or measured on-site with a GPS receiver.[35]

Item 3 West Longitude: Site A and Site B longitude; taken from a USGS topographic map or measured on-site with a GPS receiver.

Item 4 Site Elevation: Site A and Site B elevation above mean sea level, normally taken from topographic map or from field measurements with an altimeter (note some GPS receivers have an altitude readout, but readings have been found to be inconsistent and generally unreliable).

Item 5 Polarization: Either vertical or horizontal (for BETRS, normally vertical).

Item 6 Path Azimuth: From Site A to Site B and Site B to Site A, in degrees from true north and magnetic north (see Appendix F for calculation of the azimuth along the great circle route between two points). These are the bearings of the directional antennas. The magnetic bearings (in parentheses) take into account the magnetic variation at the site. This can be obtained from aeronautical charts or USGS maps. In Alaska, variation is East and must be subtracted from true bearing to obtain magnetic bearing.

Item 7 Path length: From Site A to Site B, in mi (see Appendix F for calculation of the great circle distance between two points).

Item 8 Frequency: Operating frequency for this path direction, in MHz. In trunked systems, more than one frequency will be used.

Item 9 Free-Space Path Loss: The loss as calculated from Sect. 6; this loss is adjusted according to the path characteristics. See next item.

Item 10 Path Loss Adjustments: Additive losses to the free-space path loss depending on the path characteristics. Adjustments include ground-wave loss, foliage loss, building loss, and diffraction loss. See Sect. 7 through 11.

Item 11 Total Path Loss: Item 9 + Item 10. Some path loss calculation methods do not include a separate free-space loss component or adjustment component but, instead, calculate the total loss in one operation.

Item 12 Antenna Height: Transmitter antenna height at Site A, in ft above ground level.

Item 13 Transmission Line Type: Model or type of coaxial transmission line at Site A.

Item 14 Transmission Line Length: Length of the Site A coaxial cable, in ft.

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35 Some manufacturers of hand-held GPS receivers are Garmin, Magellan, II Morrow, Trimble Navigation, and Sony.

Item 15 Transmission Line Loss: Loss of the Site A coaxial cable at the operating frequency as determined from the cable length and manufacturer's data sheet (Note: If the antenna or transmitter is poorly matched to the transmission line impedance (high VSWR), the transmission line loss may be significantly higher than given in the data sheet).

Item 16 Transmitter Power: Output power of the Site A transmitter, in dBm (Note: Power(dBm) = 10log[Power(watts)] + 30). It is important to determine if the transmitter power quoted in the manufacturer's data sheet is at the antenna connector or transmitter connector inside the radio. If it is at the transmitter connector, duplexer loss must be included in Item 18 below.

Item 17 Filter/Isolator Loss: If external filters or isolators are used at the Site A transmitter, the losses must be included here. These typically range from 0.5 to 2.5 dB.

Item 18 Other System Loss: If the duplexer loss at Site A is not included in Item 16, include it here. Also, connector losses, if significant, should be included here.

Item 19 Total Fixed Loss: Items 15 + Item 17 + Item 18.

Item 20 Antenna Gain: Antenna gain for Site A from the manufacturer's data sheet, in dBi (note: many manufacturer's show gain with respect to a dipole antenna (dBd) rather than with respect to an isotropic antenna (dBi). To convert from dBd to dBi, add 2.15 dB to the antenna gain). If the path loss calculations are made with respect to dipole antennas, use dBd in this item.

Item 21 Transmitter EIRP: Item 16 ✄ Item 19 + Item 20.

Item 22 Antenna Height: Same as Item 12 except for the Site B receiver.

Item 23 Transmission Line Type: Same as Item 13 except for the Site B receiver.

Item 24 Transmission Line Length: Same as Item 14 except for the Site B receiver.

Item 25 Transmission Line Loss: Same as Item 15 except for the Site B receiver.

Item 26 Receiver Threshold: Site B receiver sensitivity, in dBm. The value to use here is somewhat subjective, but the recommended sensitivity is that which gives 20 dB quieting, in dBm (analog FM receivers) or 1E–4 to 1E–3 BER (digital receivers). For most analog FM BETRS systems operating in the 450 MHz band, the value normally is –107 dBm, but higher or lower values may be used depending on the receiver characteristics and the desired quality of service. The recommended value for digital receivers depends somewhat on the type of modulation; values range from –99 to –111 dBm. The control channel, if used, may have different receive requirements, which should be used if they are more stringent than traffic channel requirements.

Item 27 Filter/Isolator Loss: Same as Item 17 except for the Site B receiver.

Item 28 Other System Loss: Same as Item 18 except for the Site B receiver.

Item 29 Total Fixed Loss: Same as Item 19 except for the Site B receiver.

Item 30 Antenna Gain: Same as Item 20 except for the Site B receiver.

Item 31 Unfaded Received Signal Level: Item 21 – Item 11 + Item 30 – Item 29, in dBm.

Item 32 Fade Margin: Item 31 – Item 26, in dB

Item 33 Reliability Estimate: Percentage availability taken from Table 3.

Path Loss Data Entry Form

Item	Parameter	Site A	Site B
1	Site Name:		
2	North Latitude	° ' "	° ' "
3	West Longitude	° ' "	° ' "
4	Site Elevation (AMSL)	ft	ft
5	Polarization		
6	Path Azimuth True (Magnetic)	° (°)	° (°)
7	Path Length	mi	
8	Frequency	MHz	
9	Free-Space Path Loss	dB	
10	Path Loss Adjustments	dB	
11	Total Path Loss	dB	
12	Antenna Height (AGL)	ft	
13	Transmission Line Type		
14	Transmission Line Length	ft	
15	Transmission Line Loss	dB	
16	Transmitter Power	dBm	
17	Filter/Isolator Loss	dB	
18	Other System Loss	dB	
19	Total Fixed Loss	dB	
20	Antenna Gain	dBi	
21	Transmitter ERPi	dBm	
22	Antenna Height (AGL)		ft
23	Transmission Line Type		
24	Transmission Line Length		ft
25	Transmission Line Loss		dB
26	Receiver Threshold		dBm
27	Filter/Isolator Loss		dB
28	Other System Loss		dB
29	Total Fixed Loss		dB
30	Antenna Gain		dBi
31	Unfaded Received Signal		dBm
32	Fade Margin	dB	
33	Reliability Estimate	%	
34	Date:	By:	
35	Work Order No.	Remarks:	

21. Voltage Drop Calculations

BETRS systems typically are powered either by a nominal 48 vdc power supply (central office station equipment) or 12 vdc power supply (subscriber station equipment). The following paragraphs will describe how to properly size the power feed conductors and protect them with the proper fuse (or circuit breaker) size. Some equipment are powered by a nominal 120 vac, 60 Hz supply and have internal batteries and chargers. These systems normally are factory equipped with an ac power cord and have factory wired dc power supplies. Such systems are not covered here.

There are two primary considerations when sizing power feed conductors: current carrying capacity and allowable voltage drop between the power source and the load. The current carrying capacity depends on several factors such as insulation type and whether or not the conductors are cabled or enclosed in conduit. The allowable voltage drop depends on the equipment requirements, which frequently are not stated by the manufacturer. Therefore, some general guidance will be provided here.

The powering of subscriber station equipment is governed by the National Electrical Code, in particular article 300, which describes the allowable wiring methods in buildings.

When making voltage drop calculations, it is necessary to consider the resistance of the negative and positive leads together (that is, the loop resistance). This section is concerned with dc powered systems, so only the dc resistance is required in voltage drop calculations, and it is not necessary to consider conductor reactance or other ac effects.

Common power conductor sizes are #16 AWG through #2 AWG. Only copper conductors should be used in BETRS installations to avoid the problems associated with reliably terminating small aluminum conductors.

Table 20 gives the characteristics of copper conductors in the commonly available sizes. In this table, the ampacity and corresponding fuse or circuit breaker size is given for 2-conductor SO cords as listed in Table 400-5(A) of the National Electrical Code (NEC). Cords must be used because the NEC does not allow individual power conductors in this type of application unless the conductors are enclosed in a raceway (such as conduit).

Table 20
Conductor Characteristics

AWG	DC Resistance (R_{dc}) @ 68°F (Ohms/100 ft)	Ampacity (amps)	Dia. (mils)	Area (cm)	Area (sq. in.)	Approx. Weight (lbs/100 ft)	Fuse or Circuit Breaker Size (amp)
2	0.0179	95	257.6	66,832	0.05213	20.09	80
4	0.0274	70	204.3	42,613	0.03278	12.64	60
6	0.0436	55	162.0	26,813	0.02062	7.95	40
8	0.0700	40	128.5	16,864	0.01297	5.00	35
10	0.1100	30	101.9	10,433	0.00816	3.14	25
12	0.1880	25	80.81	6,088	0.00513	1.98	20
14	0.2990	18	64.08	3,830	0.00323	1.24	15
16	0.4760	13	50.82	2,409	0.00203	7.82	10

The voltage drop across a set of powering conductors is found from:

$$VD = IR_{dc} \frac{l}{100} \tag{73}$$

where VD = voltage drop (volts), I = current (amps) and R_{dc} = dc resistance (ohms/100 ft), and l = loop length (ft). Note: The loop length is the length of the positive lead plus the length of the negative lead. The current to be used should be under the highest load condition - during off-hook, or transmit.

The maximum allowable voltage drop is shown in Table 21 for systems operating at the two most common voltages. Some specific equipment may have a higher allowable drop, but it should be the objective of all installations to minimize this drop to the lesser of the either the manufacturer's values or those shown in the table.

Table 21
Allowable Voltage Drop

Nominal Voltage	Actual System Operating Voltage	Allowable Voltage Drop, VD
48 vdc	52 to 54 vdc	2.0 v
12 vdc	13 to 13.5 vdc*	0.5 v

* The actual system operating voltage will be approximately 14.0 to 14.4 vdc if automobile type batteries are used.

Given the maximum allowable voltage drop, it is easy to determine the maximum allowable *loop* length, *l*, for a given set of conditions including conductor resistance, current and allowable voltage drop from:

$$l = \frac{100 \cdot VD}{IR_{dc}} \tag{74}$$

The length of each individual conductor, *l*', is

$$l' = \frac{50 \cdot VD}{IR_{dc}} \tag{75}$$

Fig. 28 and 29 are graphical representations of eq. (75) for each of the common voltages and with VD from Table 20. Be careful when using these graphs because the load currents do not increase by the same increment across the graph. The lengths shown in the vertical axis are cord lengths, *l*', but the calculations use loop lengths (twice the cord length, 2*l* = *l*'). An example will illustrate the use of these graphs. Assume the current draw in a 12 volt subscriber station is 0.5 amps in the on-hook (idle) state and 2.5 amps in the off-hook (busy) state. A length of SO cord 25 ft long is required between the dc power supply and the station equipment. Find the minimum wire size.

For this situation, enter the graph on the vertical axis at 25 ft and move to the right until intersection with the 2.5 A line is obtained. This occurs between No. 16 and No. 14 AWG conductor sizes. Move to the first vertical grid line to the right of this intersection, and drop down to the horizontal axis. Read the minimum required conductor size of No. 14 AWG on the horizontal axis. This conductor size (14 AWG) will provide no more than 0.5 v of drop for a 2.5 a current draw in a 12 vdc system.

Consider a 48 v system with l' = 100 ft and load current = 5.0 a. The intersection with the 5.0 a curve is between No. 14 and No. 12. Move to the first vertical grid line to the right and drop down to the horizontal axis. This conductor size (No. 12) will provide no more than 2.0 v drop at a 5.0 a load.

Fig. 28
Length vs. Conductor Size for 12 Vdc System with Voltage Drop ≤ 0.5 V

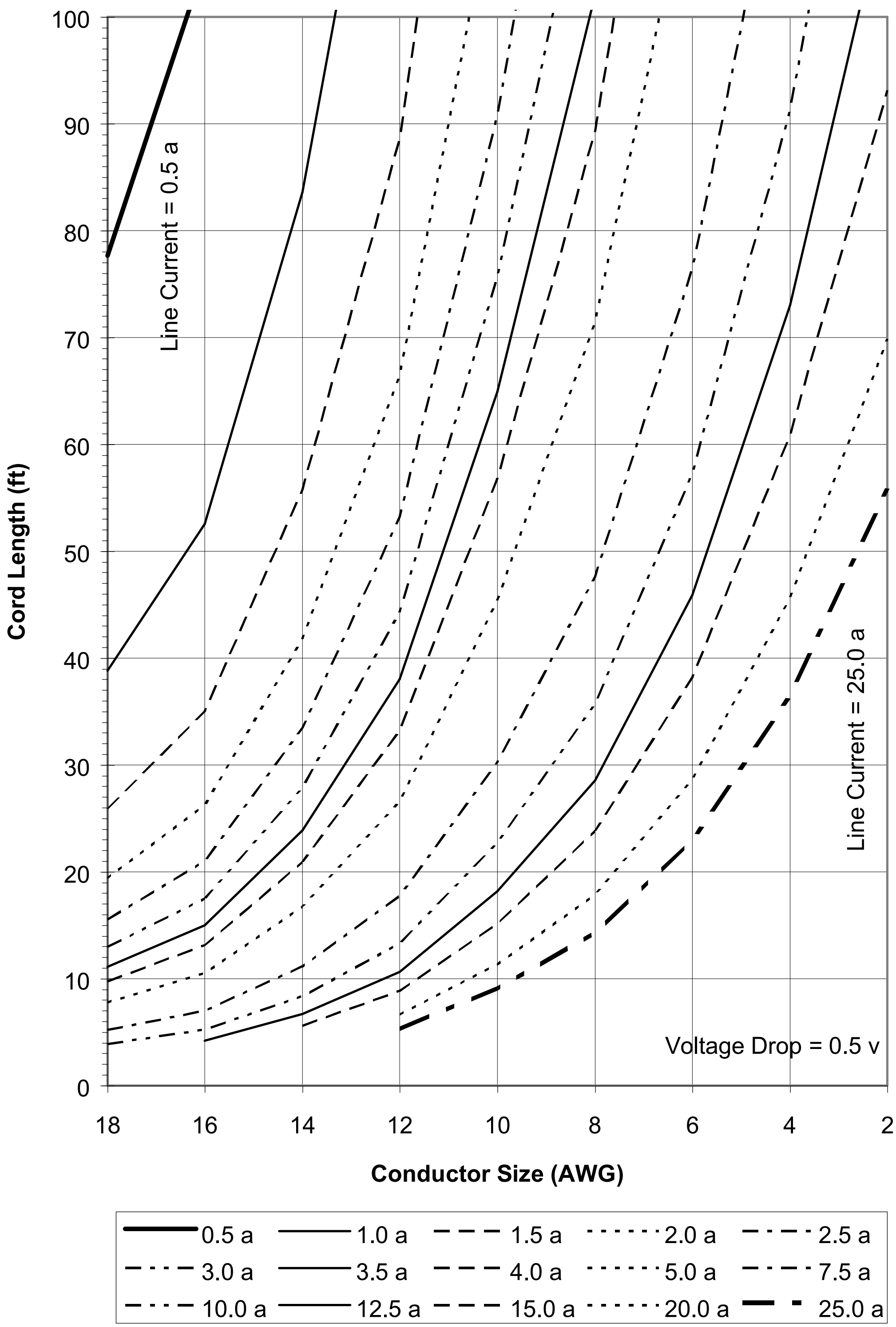
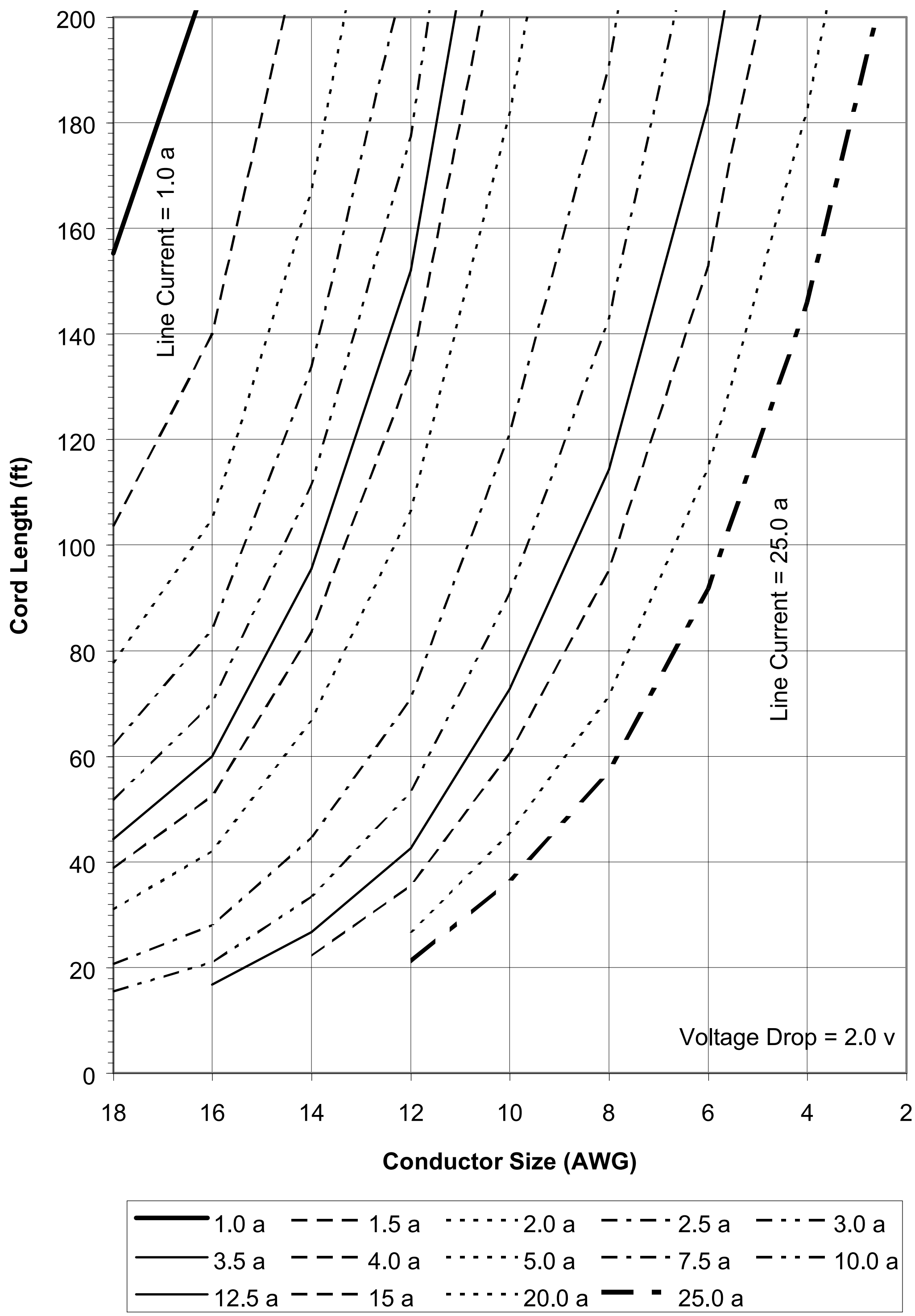


Fig. 29
Length vs. Conductor Size for 48 Vdc System with Voltage Drop ≤ 2.0 V



22. Tests and Measurements

Tests performed on BETRS systems consist of voice frequency (VF) interface tests (line seizure and release, ringing, answering, loop current, dialing, and VF signal levels) and radio frequency (RF) tests (receiver sensitivity, transmitter power and modulation). General procedures are given in this section, which need to be modified for the actual radio, interfaces and test equipment used. For example, sensitivity and modulation tests will depend on the availability and accessibility of receiver and transmitter test points and proper test equipment.

The radio manufacturer's recommended test procedures and specifications should be used when available. Where manufacturer's procedures differ from those described in this section, the manufacturer's procedures take precedence. In most cases, it will not be possible to test or align certain parts of a system without test jigs or test harnesses. These are not normally available from the manufacturers and must be shop-built.

The manufacturers of some systems may not recommend field adjustment of certain parameters because of the need for special test equipment.

At a minimum, transmitter RF power output, dialing and talk tests should be made on all radios before they are placed into service. These tests are the simplest to perform and require the least test equipment.

Most communications service monitors or communications service analyzers, although expensive, have the capability to perform an almost full test suite with a single instrument. Table 22 lists typical test equipment required to test BETRS systems. This list is not exhaustive nor is it final. Equipment models and manufacturers not listed may work as well or better.

Table 22
Typical Test Equipment[36]

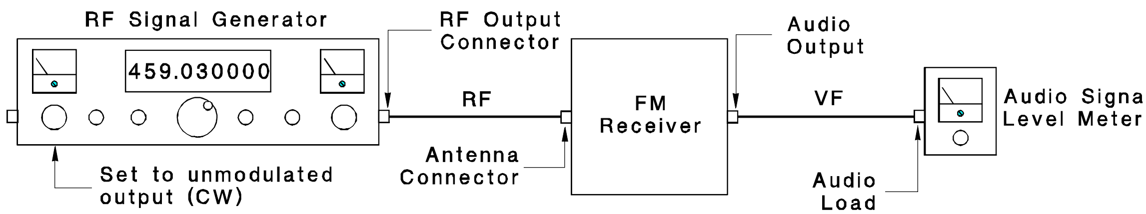
Description	Mfr. and Model	For Testing	Comments
Communications Service Monitor	Motorola R-2600 or IFR	Transmitter and receiver	Replaces RF signal generator, deviation meter and audio power meter
RF signal generator	HP 8640B	Receiver	
Audio power meter			May substitute VF transmission test set
SINAD meter	Helper CML-1	Receiver	Capable of tests with and without a C-message filter
Deviation meter		Transmitter	
Through-line wattmeter	Bird 43	Transmitter	
Dummy load	Bird 86XX or RF Industries or Celwave	Transmitter	
RF connector adapter set			
VF transmission test set	Ameritec AM-44 or AM-48	Transmitter and receiver	
Coaxial jumper cables	Shop built	Transmitter and receiver	

Receiver sensitivity tests indicate the minimum carrier level input (either modulated or unmodulated) required for a given post-detection SNR at the audio output. Sensitivity specifications for narrowband FM systems normally give 20 dB quieting and SINAD values. Receiver sensitivity tests are inconvenient to make in the field because of the amount of test equipment required.

When no signal is present at the receiver input and with the receiver audio stage unsquelched, noise will be present at the receiver audio output. When an unmodulated carrier is applied to the receiver input at the receiver frequency, the receiver output will quiet down. The amount of quieting depends on the carrier signal level. The 20 dB quieting test measures the amount of carrier required to reduce the noise power by 20 dB (0.1 audio voltage) below the noise with no carrier present. The major reason for this test is to determine if the receiver has sufficient RF and IF gain. It does not test the audio output quality. The connections for the 20 dB quieting tests are shown in Fig. 30 and the test procedures follow. Care should be taken to prevent the transmitter from keying and applying RF power to the signal generator output port. Some communications monitors may allow a limited amount of transmitter power into the RF output port.

[36] Test equipment for amateur radio applications should never be used to troubleshoot or test BETRS equipment because of frequency range and quality of the amateur equipment.

Fig. 30
Receiver 20 dB Quieting Test

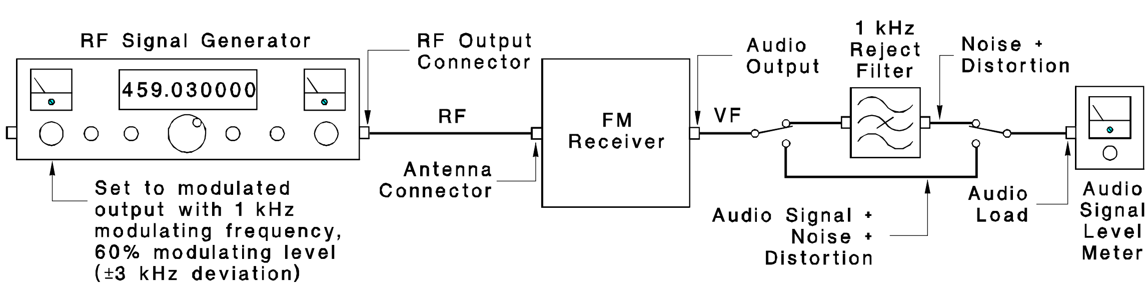


1. Connect the RF signal generator (with RF output turned off) as shown. Connect an audio power meter to terminate the receiver in its audio output impedance. Alternately, connect a properly rated resistor (resistance and power rating) to the receiver output and connect a voltmeter across the resistor.
2. Adjust the receiver squelch fully open.
3. Adjust the receiver output level control to provide an output on the audio level meter toward the high-end of the meter scale.
4. Adjust the RF signal generator output level (unmodulated) until the noise output power drops 20 dB on the power meter or 1/10 the voltage on the voltmeter.
5. The RF level in microvolts (or dBm) read on the signal generator RF attenuator is the 20 dB quieting sensitivity.

The 12 dB SINAD test determines if the receiver can recover the audio from a weak modulated input signal and reproduce it without gross distortion at the audio output. The SINAD test requires a modulated RF carrier. The test first measures the composite output signal, which includes the detected audio, signal distortion (produced in the RF, IF and audio stages) and noise. Then the audio signal is filtered out with a 1 kHz reject filter and the remaining signal containing only the distortion and noise components is measured. The ratio, in dB, is the SINAD, or Signal plus Noise And Distortion.

Since the SNR depends on the FM deviation or modulation level, a standard deviation of 60% of peak is used in the test. For BETRS systems, the allowed peak is ±5 kHz, so the test deviation is (0.60 X ±5 kHz =) ±3 kHz. Fig. 31 shows the test connections. The procedures follow.

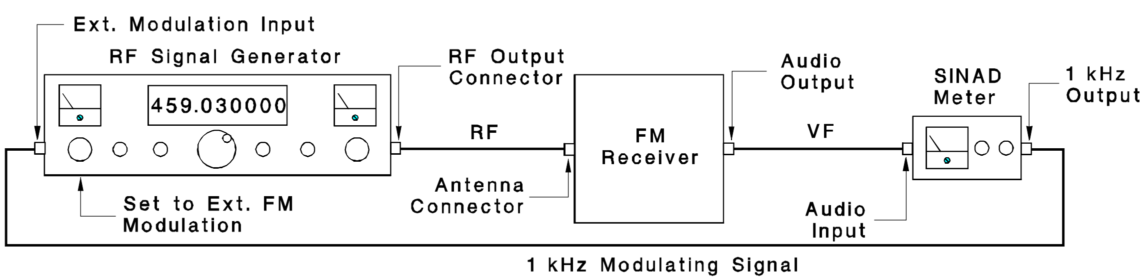
Fig. 31
Receiver SINAD Test



1. Connect the RF signal generator as shown. Set the generator output for 1,000 μv with 1 kHz modulating tone and ±3 kHz deviation (60% of 5 kHz maximum allowed). Connect the audio power meter to terminate the receiver in its audio output impedance through a double-throw switch. The 1 kHz reject filter is connected to the other switch pole as shown. (SINAD meters have a built-in filter and switches.) Set the switch to bypass the filter.
2. Adjust the receiver output level control to provide an output power at least 50% of rated output power. Note the power reading.
3. Switch in the 1 kHz reject filter (to filter out the 1 kHz modulating tone). If the filter is tunable, adjust it for minimum reading on the audio power meter. The drop is audio power should be at least 12 dB.
4. Lower the RF level until the audio power meter reads exactly 12 dB below the level noted in step 2 above. If the audio output is less than 50% of rated, increase the RF level until the audio power is 50% of rated output.
5. The RF level in microvolts (or dBm) is the 12 dB SINAD sensitivity of the receiver.

The SINAD test is most easily done with a test meter specifically designed for the purpose. When using a special SINAD meter, the connections are typically as shown in Fig. 32. The procedures are very similar to those previously described. The 1 kHz tone from the SINAD meter has an adjustable output and is used to modulate the RF signal generator. The deviation is set to ±3 kHz as before.

Fig. 32
Receiver SINAD Tests with a SINAD Meter



Transmitter RF power output tests are straight-forward, requiring only a 50 ohm dummy load and through-line wattmeter for bench tests.[37] The wattmeter should have the appropriate plug-in elements rated for both the frequency and power level to be measured. The dummy load is used to check the transmitter under matched loading conditions and should have a continuous power rating equal to or greater than the rated transmitter power output.

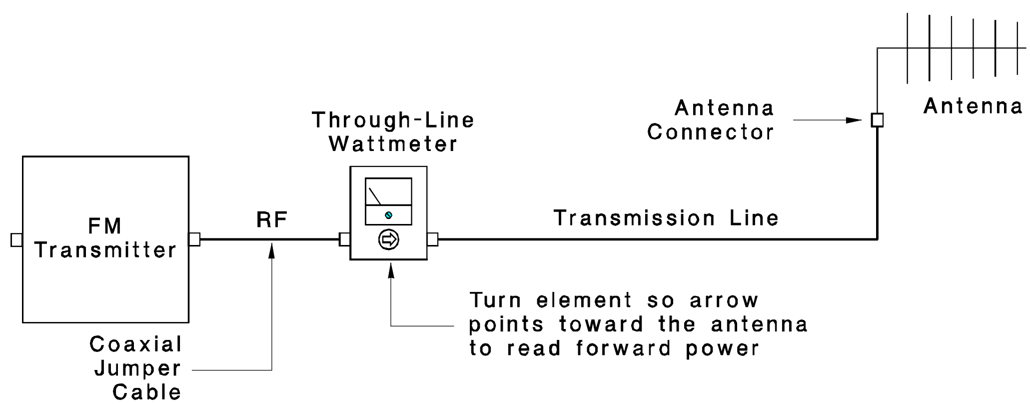
Field measurements include the actual coaxial transmission line and antenna used, and the dummy load may not be required except for troubleshooting purposes. Transmitter RF power

[37] The Bird model 43 Thru-Line and Sola Basic Dielectric model 1000 R.F. Wattmeter are two similar portable units that use plug-in elements. The Telewave Broadband R.F. Wattmeters model 44L1 (2 - 200 MHz) and model 44A (25 - 1,000 MHz) are portable units that do not use plug-in elements.

output tests should be performed upon initial installation of both central office and subscriber station equipment and anytime problems with these installations are suspected. The RF power output of an FM transmitter is independent of the modulation level; that is, the wattmeter reading should not change from zero to full modulation.

The connections for measuring RF power output into the transmission line and antenna are shown in Fig. 33. With a through-line wattmeter and the connections as shown, the forward power delivered into the transmission line is measured when the wattmeter element is pointed to the right. The reflected power is measured when the element is pointed to the left.

Fig. 33
Transmitter RF Power Output Measurement



The ratio of reflected power to the forward power is an important ratio because it indicates the degree of matching between the transmitter, coaxial transmission line and antenna impedances. A perfect match, and no reflected power, means all the power developed in the transmitter is delivered to the antenna and, except for losses in the antenna, is radiated into space.

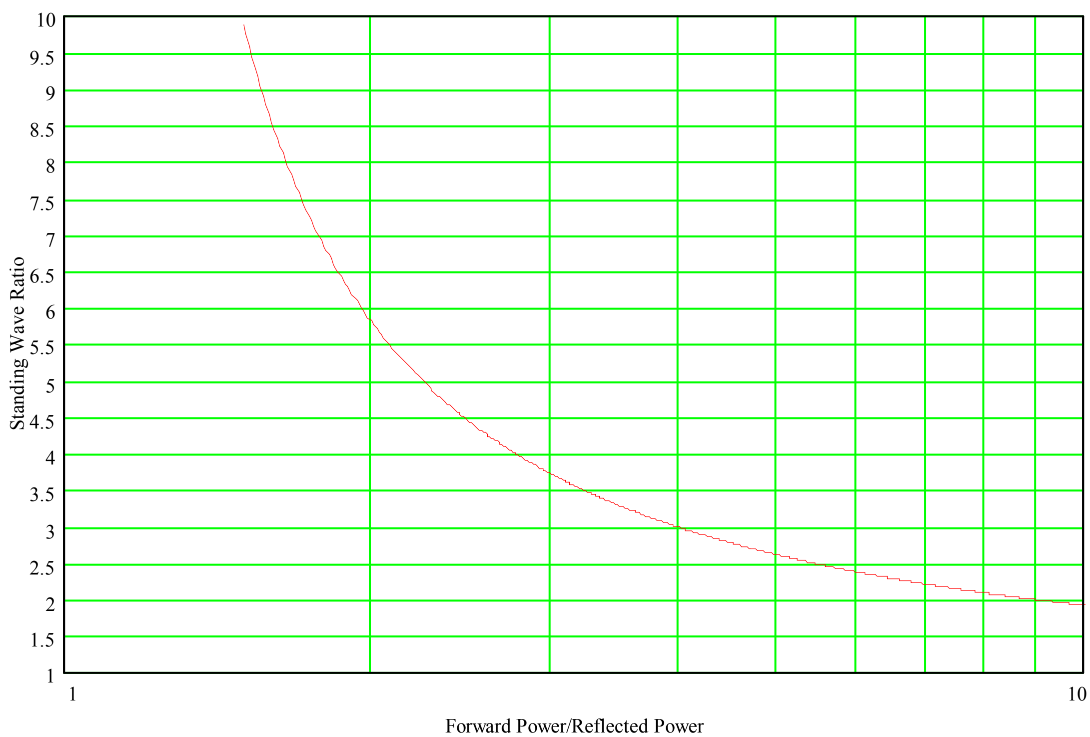
The voltage standing wave ratio, or VSWR, relates the reflected power P_R to the forward power P_F as follows (all powers are in linear units such as watts):

$$VSWR = \frac{1+\sqrt{P_R/P_F}}{1-\sqrt{P_R/P_F}} \quad (76)$$

Eq. (76) is plotted in Fig. 34 for P_F:P_R = 1:1 through 10:1 and in Fig. 35 for P_F:P_R = 10:1 through 1,000:1. In general, the lower the VSWR, the better, with a VSWR = 2 considered acceptable in BETRS applications.[38] This is a ratio of P_R to P_F of approximately 1/8 or, conversely, P_F:P_R = 8:1. For example, if the forward power is measured as 2 watts and the reflected power is measured as 0.25 watts, the ratio is 8:1. The ratio is important, not the actual magnitudes. Any other power values with a ratio of 8:1 give a VSWR =2.

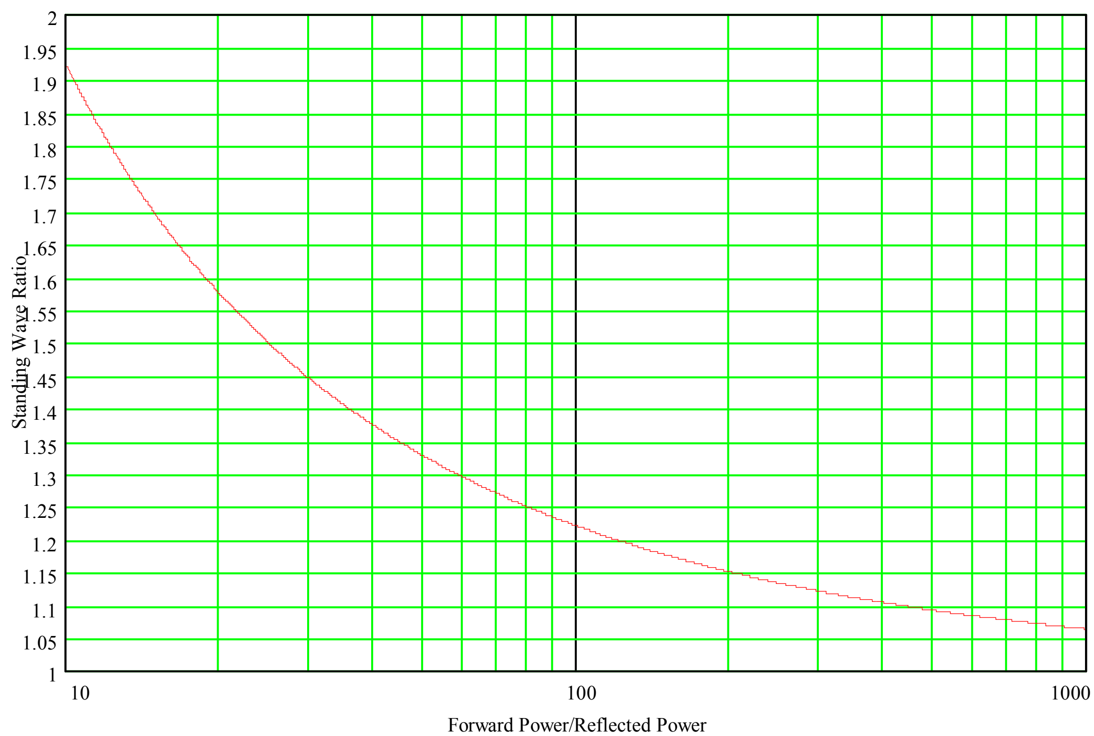
[38] Note this is different than the 1.5 VSWR, which is maximum allowable for the antenna alone.

Fig. 34
VSWR versus the Ratio of Forward Power to Reflected Power (Ratio = 1 to 10)



It is important to note that VSWR measurements at the transmitter end of a transmission line will be misleading if the line loss is high (either by design or because of damaged cable or poor connection at the antenna). The transmitter RF output is reduced by the line loss to the reflection point (damaged area or antenna) and the reflected power is again reduced by the line loss giving an artificially low reflected power reading at the transmitter. Therefore, if the transmission line has significant loss, the VSWR calculated from the power ratios at the transmitter will be better (lower number) than the VSWR that exists at the antenna.

Fig. 35
VSWR versus the Ratio of Forward Power to Reflected Power (Ratio = 10 to 1,000)



From a propagation point of view, it is the VSWR at the antenna that is important because it measures the effectiveness of the match between the coaxial cable transmission line and the antenna impedances and, therefore, the power delivered to the antenna. The VSWR at the antenna can be found from the following expression if the line loss is known:

$$VSWR\ (antenna) = \frac{1+\sqrt{2\,LP_R/P_F}}{1-\sqrt{2\,LP_R/P_F}} \tag{77}$$

where the forward and reflected powers *are measured at the transmitter* and L is the one-way transmission line loss expressed as a linear value (not dB). Eq. (77) is plotted in Fig. 36. If the line loss is known in dB, it can be converted to a linear value by:

$$Line\ Loss(linear) = 10^{[L(dB)/10]} \tag{78}$$

For example, a line loss of 2 dB expressed as a linear value is $10^{0.2} = 1.58$.

When it is necessary to measure the transmitter RF power on the bench, or if radiation from an antenna is not desirable during a transmitter test, the connections shown in Fig. 37 can be used. The dummy load absorbs all the transmitter power. Well designed and properly tuned transmitters will show VSWR = 1 when the forward and reflected power is measured at a dummy load (the reflected power will be immeasurably small).

Fig. 36
VSWR at the Transmitter versus VSWR at the Antenna for Various Line Losses

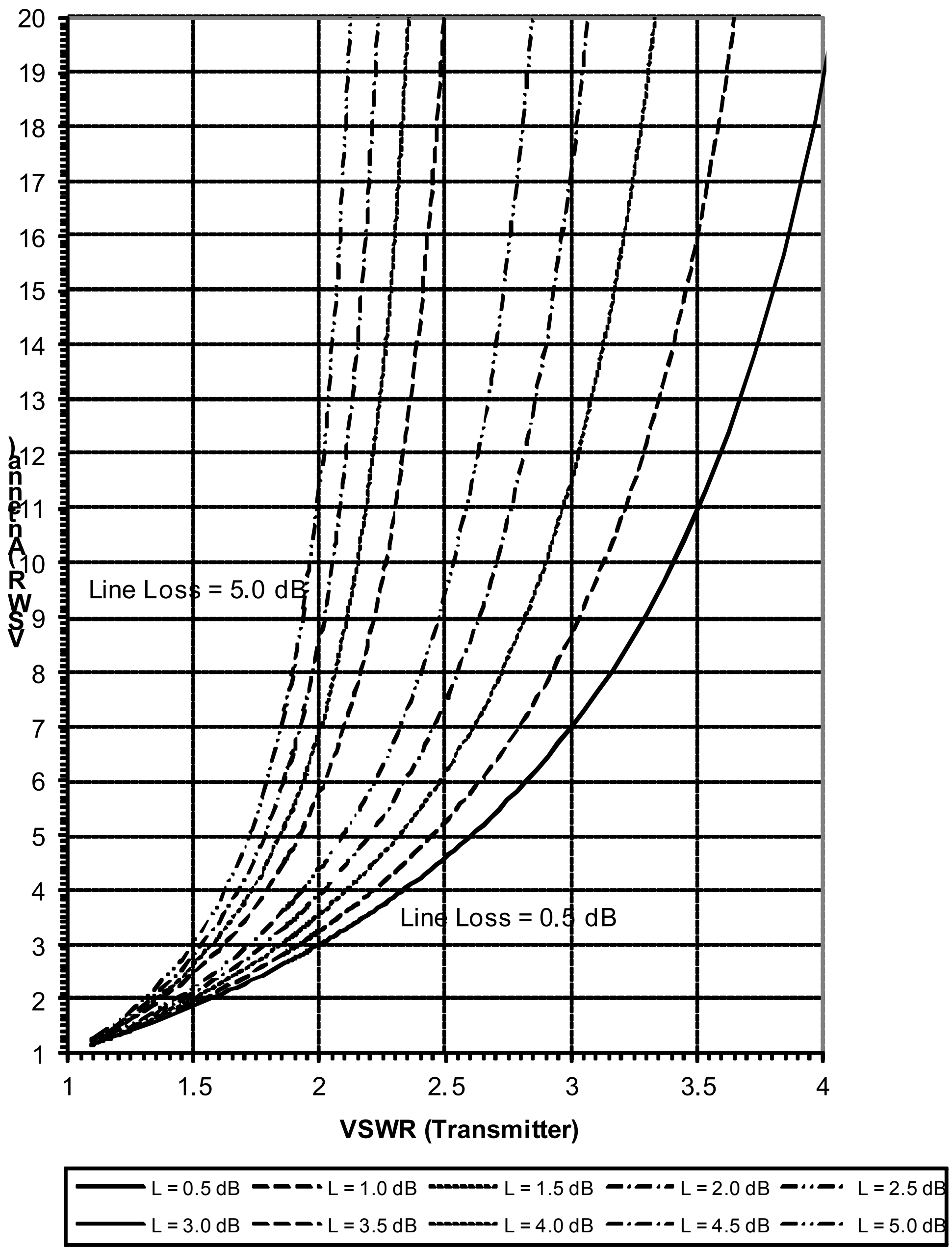
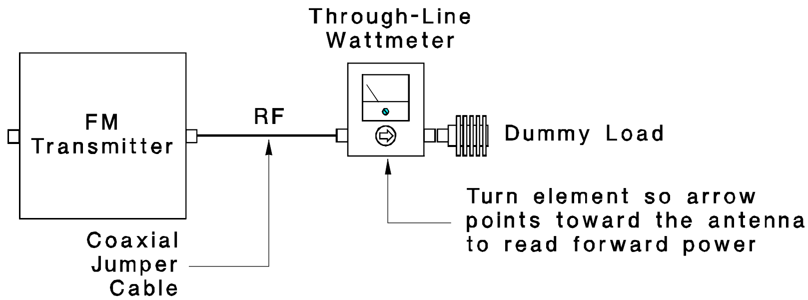


Fig. 37
Transmitter RF Power Measurement with a Dummy Load



In addition to the above described RF tests, the loop current supplied by the subscriber station to the telephone set should be tested. This can be done by placing the test leads of a digital multimeter set to the current range across the tip and ring of the interface jack. The minimum current usually is 20 ma, although telephone sets designed according to EIA-470 require at least 23 ma. While this is a good go/no-go test, it does not take into account the telephone set and drop or station wire resistance. A better test is to check the installation by putting the digital multimeter (again set to measure current) in series with either the tip or ring lead of the station wire and taking the telephone set off-hook. Again, the current should be at least 23 ma.

After the a subscriber installation is completed it must be tested using a live call. Calls also should be made to the central office milliwatt and quiet termination numbers for loss and noise measurements. Most central offices in Alaska use NXX-1102 for the milliwatt and NXX-1100 for the quiet termination. The insertion loss of BETRS radio systems are 2 to 3 dB, so the milliwatt signal will measure −2 to −3 dBm. Noise should measure less than 20 dBrnC.

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Notes:

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- ⊗ Available from *Ask IEEE*, 800-949-4333.
- · Available from Global Engineering Documents, 800-854-7179
- 🕮 Available from US Government Printing Office, 202-783-3238
- ☎ Available from USDA, Rural Electrification Administration, Washington, DC, 202-720-1255.
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- ↑ Available from National Fire Protection Association, Quincy, MA, 800-344-3555.
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