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TWTs: GREAT BANDWIDTH AND LARGE POWER GAIN

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ABOUT THE COVER

The traveling-wave tube (TWT) is a complete RF amplifier in a vacuum envelope. It features great bandwidth and large power gain. The TWT installed in the front compartment of this microwave amplifier is an E-R Research Labs Model 514 X-band TWT. *(photo courtesy of Bob Atkins, KA1GT)*

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3) support efforts to advance the state of the Amateur Radio art.

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Both theoretical and practical technical articles are welcomed. Manuscripts should be typed and double spaced. Please use the standard ARRL abbreviations found in the 1985 and 1986 ARRL Handbooks and in the January 1984 issue of *QST*. Photos should be glossy, black-and-white positive prints of good definition and contrast, and should be the same size or larger than the size that is to appear in *QEX*.

Empirically Speaking . . .

Parlez-Vous Nippon-go?

This may be pushing things, but it's time to think ahead about language translation. It seems to come as a surprise to some that many people in the world don't use English. We're hams, aren't we, and doesn't every ham have to learn English to get on the air? Au contraire, ozone breath! Give a listen on the so-called "foreign phone" bands and you'll hear some long-winded QSOs in Spanish, French and other tongues. Some of these stations never work English QSOs on phone and others use English only for brief exchanges of the contest variety. The latter is not really English but a structured language all of its own. If you doubt it, take a recording to an English teacher and get educated.

This is not about Wham-bam-ese but real communication. You don't think there's much exchange of ideas on the bands? Certainly there is enough perfunctory and inane chatter on the bands; every community has its neighborhoods needing beautification, and Amateur Radio is no exception. However, if you haven't heard any really deep conceptual interchange on the bands, you're not tuning to the right spots. Such exchanges have been fairly routine between serious packeteers since the early 80s. Besides, they bat a lot of weighty prose back and forth on some of the landline data networks. And, if you hunt around, you'll find some thoughtful conversation on the CW and phone bands. So, it's not just a packet phenomenon.

What packeteers are discovering is that there are some smart guys on the other side of the pond who they like to talk to but don't communicate too well, or at all, in English. Japan is a hotbed of packet activity. Until now, most of their packet debate has been a delayed version of ours. But that delay is now an instant replay as the issues they're concerned about parallel those in the US. There are signs that the Japanese will move ahead of us on some issues that have more significance for them. It probably wasn't so bad when the Japanese had to read our English Amateur Radio literature to keep up. This is because a number of Japanese engineers and businessmen have some familiarity with English as it is an international technical and business language. In other words, the Japanese have a few people at strategic places who can function in English and translate into Japanese for those who can't.

There was a time when technical papers written by Japanese engineers were prepared in English to be published in IEEE and other technical literature to have any impact. This is no longer true, in that there is now a wealth of Japanese-language engineering literature. Japanese engineers found that they had all the audience they needed by publishing in Japanese technical journals. Thus technical articles from Japan in English are drying up. There appears to be a similar trend in Japanese Amateur Radio technical writing. Now the shoe is on the other foot. Save a few places in California, the US does not have many people who can converse in technical Japanese. So we have a problem keeping track of the technology coming from the JAs.

QEX is no exception. We'd like to publish some English translations of Japanese technical articles on FAX, packet and other specialties. If you know someone who can translate technical Japanese to English, please give us a call. We can be very friendly!

But there's another dimension, ie, on-the-air translation. Wouldn't it be useful to have some translation stations? Right now this could be done manually, for example by a bilingual packet operator who would like to serve ham radio in this way. Eventually, we need to apply artificial intelligence (AI) to a translation node in the international packet network. Sure, computer language translation is pretty crude at the moment, but it's better than nothing, even without AI. Even with the worst translation programs, the output is good enough to get some idea whether the subject is of real interest to you. Of course, an AI packet translation node is a long-term project. If even minimally successful, amateurs could pioneer something that could be standard international telecommunication practice in the next century.—W4RI

New Directions in Amateur HF Data Transmission Systems—Part 1

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Amateur Radio operators have a long history of working with data transmission on the HF bands. After all, the Morse code is a form of data transmission. From that modest beginning, we progressed to RTTY using the Baudot code and mechanical printing devices, and more recently, to AMTOR (*AM*ateur *T*eleprinting *O*ver *R*adio) and packet radio. The AX.25 protocol used in the latter technique has ushered in a new era of essentially error-free communications. This development is particularly noteworthy because it allows nontextual data, such as computer programs, to be transmitted without error over long distances. In spite of these achievements, there remains room for further growth. Many advances have taken place on the professional side of HF data transmission, which amateurs have been slow to recognize and take advantage of. This article surveys some of these developments and looks at how they might be applied to amateur communications. As implied above, the emphasis is on techniques applicable to computer-to-computer data communications, rather than the more casual keyboard-to-keyboard traffic that has prevailed in the past. As a preface to this survey, we begin by examining some of the HF data transmission systems and protocols that are either currently in use or have been proposed for use on the amateur bands.

Requirements

Before beginning our survey, let's consider what attributes are important in an HF data transmission system. (The use of the term *system* here includes not only the data link protocol, but also the associated modems, radio equipment, and so on, required to implement it [levels 1 and 2 of the OSI model for you networking types].)

1) *Good efficiency.* When operating conditions are good, the system should have high throughput, with a minimum of overhead bits. Throughput should degrade "gracefully" when conditions deteriorate.

2) *Low undetected error rate.* The occurrence of a transmission error that goes undetected, and thereby uncorrected, should be an extremely rare event. Detected errors must be corrected rather than just "erased."

3) *Robustness and reliability.* The system should be tolerant of a variety of impairments, such as multipath propagation, atmospheric noise, and interference from other stations.

The AMTOR System

AMTOR has become quite popular since its introduction nearly five years ago. The main advantage of using AMTOR over conventional RTTY is AMTOR's ability to detect transmission errors and call for a retransmission of the corrupted data. It implements an ARQ (*A*utomatic *R*epeat Re*Q*uest) protocol to ensure error control. Nevertheless, AMTOR, and the CCIR standard upon which it is based (Recommendation 476-2), are far from the state of the art in HF data communications. The constant-ratio code (also known as the Morse code), and the van Duuren ARQ technique, which form the basis for the CCIR standard, have their roots in the 1930s. The code is primitive by modern standards. An analysis of the code by Sommer states that, "the relatively poor ability of the code. . . to detect errors is not of real concern when used in systems such as AMTOR, where information of a non-critical nature is being communicated."[1] The short transmission length and long turnaround time also make the technique inefficient. Dijak similarly concluded that AMTOR has its place in conversational-type communications, but its limitations make it a poor choice for computer-to-computer file transfer.[2]

The AX.25 Link Level Protocol

In contrast to conventional RTTY and AMTOR, AX.25 is based on a standard (CCITT Recommendation X.25) specifically designed for computer-to-computer communications. AX.25 was not designed for use on HF, although it is being used successfully there. Its popularity continues to increase as the price of AX.25 Terminal Node Controllers falls. The HF links that have been established between widespread packet bulletin board systems have become a workhorse in moving error-free traffic beyond the limits of the VHF/UHF packet networks. The HF links, however, are not capable of handling huge volumes of traffic, like megabyte files, because of insufficient bandwidth. Satellites and expanded UHF/microwave links must be developed to meet these requirements. It is probably safe to say that HF will always play a role in amateur data communications, both as a back-up to these higher-capacity (but more vulnerable to failure) systems, and for extending the network into remote areas where setting up a satellite station may not be feasible.

Having convinced ourselves that HF data transmission will continue to be of considerable importance in amateur circles, we must now face the reality that the present HF AX.25 links do not perform very well. The reasons why this is so can be broken down into three main areas:

1) The AX.25 protocol is unsuitable, in some respects, for the HF environment.

2) There are difficulties in applying the networking concept of multiple-access (channel-sharing) to the HF environment.

3) Problems exist with the modulation schemes and reception techniques used to transmit the AX.25 frames over HF channels.

Let's first consider the protocol. Error control (discussed later) is an important issue in protocol design. If the data transmission system is to be useful for anything other than casual conversation, the rate at which undetected errors creep into the data during transmission must be extremely small. AX.25 appears to be adequate in this regard.

Another important aspect of protocol performance is throughput efficiency. AX.25 does not fare well in this area, because of the large amount of overhead bits (bits other than information bits) contained in every packet. The overhead amounts to 152 bits, of which 112 are call-sign information, assuming a point-to-point link without digipeaters. This is not a serious penalty when maximum-length packets (256 x 8 = 2048 information bits) are transmitted. Unfortunately, on HF channels the probability of receiving

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[1]Notes appear on page 9.

a packet without errors falls off rapidly with increasing packet size. In practice, shorter packets are normally used. The overhead then becomes an appreciable fraction of the total packet length, and the throughput suffers accordingly. AX.25 is unable to take full advantage of longer, multiple-frame transmissions, which reduce the overhead because of turnaround time (transmit/receiver switching and transmission of ACK packets). This limitation results from the lack of a selective repeat capability in the protocol (more on this later).

The next reason AX.25 performs poorly on HF packet links is more a function of usage than protocol design. Packet allows the sharing of channels by virtue of its CSMA (carrier-sense multiple access) capability. Users tend to congregate on a small number of channels, which is not in itself a bad thing. For low-density traffic like keyboard-to-keyboard chit chat, it makes more efficient use of the limited HF spectrum available. Even for transmission of larger amounts of data, such as file transfers, the lower throughput, as a result of channel sharing, may sometimes be acceptable. Unfortunately, rather than degrading gracefully, the throughput tends to rapidly fall to zero as the number of users on the channel increases. The reason for this is that the collision avoidance mechanism is imperfect. Collisions occur for many reasons. The colliding packet that zaps yours may come from a "hidden" station in your skip zone, or because a fade caused the carrier detect to fail momentarily. Carrier detect circuits need a certain amount of time to respond; you and the other station may have both started to transmit during that response time "window" (a clever retry algorithm can help to prevent such repeated collisions). Possibly the other station's receiver is mistuned and isn't detecting your signal. Whatever the reason, collisions in multiple-access channels are a major impediment to achieving reasonable throughput.

It should also be mentioned that it is often unclear, particularly to newcomers, how to set TNC parameters for best performance on HF. Keep packets short (80 characters or less), and send only one or two frames per transmission. Optimum parameters vary with conditions. There is considerable latitude here for experienced operators to "fine tune" their TNC parameters as conditions change. Newcomers should check with experienced HF packet operators to learn what works best. Some aspects of HF propagation, such as the MUF for a given path, are fairly predictable. One question, especially for the HF BBS operator, is the extent to which optimum TNC parameters can be predicted and included in their forwarding files, or perhaps even adapted dynamically.

Finally, we come to the modems and associated RF systems used in HF AX.25 systems. HF modem design and receiving techniques are discussed later. Suffice it to say at this point that the Bell 103-type 300-bit/s modem is a relatively mediocre performer on HF channels.

Error Control

As stated earlier, one of the prerequisites for successful data transmission systems is an effective error control strategy. Error control techniques can be classified in two basic areas:

1) *Error detection coding/retransmission techniques*. Usually known as ARQ in these techniques, the receiving end detects the errors in a data block and calls for retransmission of the block until it is received error-free.

2) *Forward error correction (FEC) coding techniques*. The receiving end is capable of correcting at least a portion of the transmission errors without the need for retransmission of the corrupted data.

Both error-control methods are made possible by the inclusion of additional data bits in the transmission (increasing the redundancy of the data). FEC schemes typically need a much higher degree of redundancy than ARQ schemes. In some cases, an error control technique is not purely ARQ or FEC, but is a "hybrid" scheme containing elements of both. Since AX.25 is a good example of the use of ARQ error control, it is valuable at this point to examine its performance in some detail. We will then return to a more general discussion of error control.

Dijak previously analyzed how the AX.25 protocol controls errors. He compared it with HERMES, his proposed protocol that incorporates FEC techniques. His article leaves the impression that the error detection performance of AX.25 is somewhat marginal, in that it appears to be badly outclassed by that of HERMES. His analysis, however, also has shortcomings.

Errors in an AX.25 frame are detected by means of a CRC-16 code (16-bit cyclic redundancy check). Without detailing the method used, 16 redundant bits (check bits) are calculated and appended to each block of data (information bits). The values of the 16 bits depend in a complicated way on the values of the information bits. In general, if an information bit were to change, several of the check bits would also change. This means that if a transmission error occurred in a particular information bit, the error would go undetected only if exactly the right (or wrong, depending on the communicator's point of view!) pattern of errors occurred in the redundant bits. Such an event is highly unlikely.

The probability of falsely accepting an invalid data block (ie, undetected error rate), as computed from the equation given in the appendix of Dijak's article, is stated to be 0.00153×2^{-16} for all circumstances. This statement is incorrect and gives a misleading picture of the code's error detection performance. The undetected error probability for a block code is not a single number—it is a function of channel bit-error rate and the block length. The equation given allows calculation of the undetected error probability for the situation in which all error patterns are equally likely, ie, when the bit error probability is 0.5 (in other words, when there is no signal, just noise). For some codes, the equation gives an upper bound to the undetected error rate. As it happens, the CRC-16 code used in AX.25 is not one of these codes; however, it is a good approximation to the upper bound, except when the block size is extremely short.[3] More important to this discussion, the undetected error probability improves dramatically when the bit error rate is decreased to levels normally encountered on the HF bands when conditions are reasonably good (assuming the modem is designed for HF!). For example, for Dijak's minimal frame packet (16 data bytes), the undetected block error probability is less than 10^{-8} when the bit error rate is 10^{-3}. At these levels, undetected errors can be regarded as nonexistent. It is true that the undetected error rate deteriorates as the bit error probability approaches 0.5, but operation in this region can easily be avoided by implementing some type of signal quality detector. (Part two of this article will have a discussion on "soft-decision" decoding.) I have had experience using a CRC-8 error detection code on packet-type HF communications. Even with that shorter, less powerful code, undetected errors were never a problem.

The notion of being able to correct errors without resending the data is certainly an attractive one, and in some cases, it may be the only means of error control available. Error-correction coding has been the subject of intense research over the last few decades, and has indeed found a number of applications, from deep space probes to consumer electronics (eg, compact disc players). It is significant, however, that in situations in which a good feedback channel exists from the receiver to the data source, error-correction coding is almost never used. This is particularly true for channels in which the errors tend to occur in bursts, such as telephone and HF channels. The basic problem here is that, in order for an error-correction code to be effective, its design must be carefully matched to the characteristics of the channel on which it will be used. Thus, error-correction coding has been successful, for example, on the deep space channel whose behavior is very much like the classical

Gaussian channel. The most noticeable characteristic of the HF channel, on the other hand, is that it is always changing! The code that works well for you now might be useless five minutes from now.

Observations of data transmitted over an HF channel typically shows periods of nearly error-free copy, punctuated by shorter intervals with dense bursts of errors. This behavior results from fading on the channel, plus the distinctly non-Gaussian nature of atmospheric and man-made noise sources. The burst length and error-free gap statistics vary widely, making optimal error-correction code selection difficult. A code that is powerful enough to handle most of the bursts will have a tremendous overhead in terms of parity bits, most of which are "excess baggage" that get in the way of throughput most of the time (when the errors are few).

In marked contrast to the error-correction system, a well-designed ARQ system is relatively insensitive to channel characteristics. The basic philosophy of the ARQ system is simply to pump as much data as possible through the channel while the channel capacity is high, and to bide the time during the periods of low capacity, which are characterized by dense error bursts. Why beat your head against the wall? Wait a few seconds, and the channel will probably improve! The idea of making a system adaptive to different conditions by having a choice of error-correction codes available has some merit, but it is difficult to make this concept work well in practice. Selection of the best code, and communication of the choice to the receiving end of the link, is a serious problem, whether it is done automatically or by human operators. It detracts from what should be the fundamental philosophy of any system design: Keep it simple!

These views are not simply one opinion, but a widely held viewpoint among persons knowledgeable in the field of coding theory. For example, G. D. Forney, Jr, one of the leading coding theorists, has written, "in actual practice many ARQ systems are dramatically superior to any forward error-control systems in the following respects: They have much higher data throughput, and are substantially error free."[4] ARQ systems are (or can be) easy to implement, robust, and effective. That is not to say that any ARQ protocol, such as AX.25, will be effective on HF channels. There are several ways to improve the performance of a straightforward ARQ system for HF use, and error-correction coding can play a useful role. The next several sections survey some of these techniques; then we'll return to the question of designing (or adapting) an ARQ protocol for this application.

HF Channel Characteristics and Modem Design

Although successful packet radio communications take place in the HF bands, the performance of the present AX.25-based system is highly erratic. Modem design is a large part of the problem. Many are not capable of reliable communications on HF channels at a data rate of 300 bit/s. Signaling with binary FSK at this rate produces a symbol length (bit duration) of 3.3 ms. Unfortunately, the signal received at the far end of the link does not usually arrive by means of a single ionospheric path. Instead, it is a superposition of several replicas of the transmitted signal which have travelled by different routes, and consequently arrive at slightly different times. This phenomenon, known as *multipath propagation*, is virtually always present to some degree, and destructive interference between the multipath components gives rise to fading conditions.

Figs 1A through 1D show some of the major mechanisms that produce multipath propagation. To begin with, the ionospheric layers involved in skywave propagation do not act as mirror-like reflectors. The layers are actually diffuse areas of varying ionization density; because of this complex nature, it is possible that radiation leaving a transmitting antenna at two different elevation angles can follow different paths through the layer, and still arrive at the same receiving location (Fig 1A). The earth's magnetic field also plays a part. Its presence in the ionized layer causes the electrons set in motion by the incident electromagnetic field to generate two waves, known as the *ordinary* and *extraordinary* waves. This phenomenon is shown in Fig 1B, and is referred to as *magnetoionic splitting*. Since they interact differently with the ionized medium, the two components follow different paths in their journey to the receiving antenna.

Another common source of fading, especially during the daylight hours, is *multilayer propagation*. Fig 1C shows a typical example of the E and the F2 layer. Part of the transmitted energy propagates via a one-hop E-layer path. But unless you are operating well below the E-layer MUF for that path, there exists a cutoff angle such that the transmitted energy radiated above this angle penetrates the E layer and reaches the F2 layer. Some of the misdirected energy is reflected to the receiving site to produce a second path with a greater propagation delay (up to a few milliseconds) than the first.

Multihop propagation is an essential ingredient in long-haul HF communications. Fig 1D shows that even when a link is within a one-hop range, multihop components are most likely to interfere with the one-hop signal. It could be argued that the two-hop signal is always much weaker than the one-hop signal, since there are at least three valid reasons why the two-hop signal has a higher path loss. The signal travels a longer distance, it travels through the absorbing D layer more times, and it is exposed to attenuation caused by ground reflection. The two-hop signal (and higher-order modes), nevertheless, can be surprisingly close to the one-hop signal in strength. Often the distance loss (always less than 6 dB for the case shown) is the only sig-

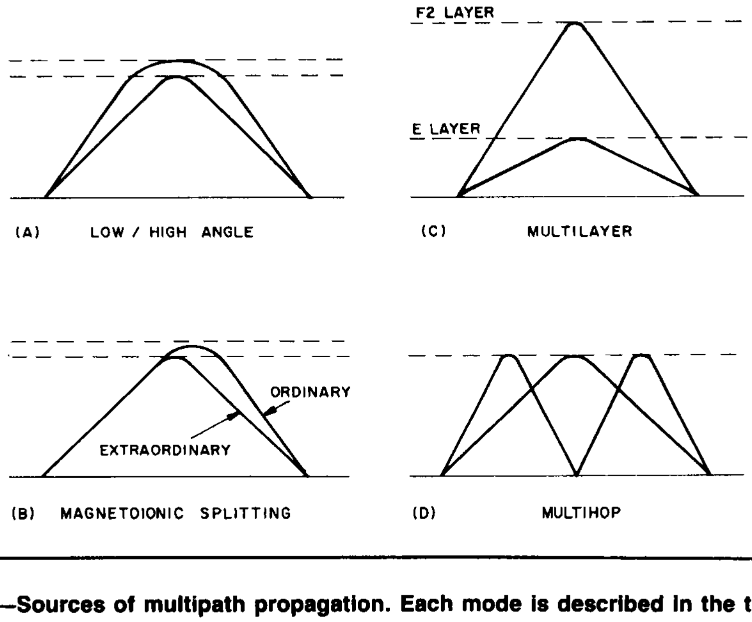

Fig 1—Sources of multipath propagation. Each mode is described in the text.

nificant difference. D-layer absorption may be absent (eg, at night), but even when it is present, the absorption is less per hop for the higher-angle two-hop mode than for the one-hop signal that passes through the layer more obliquely. This tends to cancel the difference.

The attenuation caused by ground reflection is typically in the range of 1 to 6 dB for ground with very poor conductivity, and less than 1 dB for seawater or ground with high conductivity.[5] Add to this an antenna pattern that favors the higher angle of arrival of the two-hop mode, and it's easy to see how the two multipath components can arrive at the receiver with almost the same strength. When conditions are right, higher-order multihop modes can contribute significantly to the severity of the fading as well.

The tool used by ionospheric physicists to study the reflecting layers is called an *ionospheric sounder*, or *ionosonde*. An ionosonde fires pulses of swept-tone signals into the ionosphere. A receiver synchronized to transmitter-frequency changes receives and records the echoes. The receiver may be at the transmitter site (vertical-incidence sounding), or at a separate site (oblique-incidence sounding). The output in either case is a plot called an *ionogram* (Fig 2), which shows the intensity of the received echoes versus time delay (usually converted to an equivalent layer height) and frequency. An ionogram is a graphic display of the degree of multipath propagation that exists at a given frequency; in particular, multihop returns appear as additional layers at multiples of the height of the real layers that cause them. I have seen many ionograms (vertical-incidence) where the echoes had significant strength after undergoing *six or seven hops*! It was not possible to determine the number of hops at which the echoes became negligible, because the time delays exceeded the maximum scale of the ionogram. (The maximum is typically an equivalent layer height of 1000 km, corresponding to a time delay of 6.7 ms.)

In general, multipath propagation is a complex mixture of several of the different mechanisms just described. Furthermore, the situation is dynamic rather than static, and the amplitude and phase of each of the multipath components vary independently of the others. The behavior of the received signal (the sum of several nonstatic components) is therefore rather complex. Antenna elevation patterns at both ends of the link also play an important part in determining the effect of multipath propagation resulting from multilayer and multihop propagation, especially on the shorter links where the differences in angle of arrival of the various components can be appreciable.

The amount of fading present on received signals is measured by the *multipath spread*. This parameter is essentially a statistical measure of the time period over which significant energy from a given transmitted signal element arrives at the receiver. The crux of the matter is how multipath propagation affects HF data transmission. To examine this, we must distinguish between two cases that depend upon the relationship between the multipath spread, which we shall call T_m, and the symbol duration (baud length) T of the data signal.

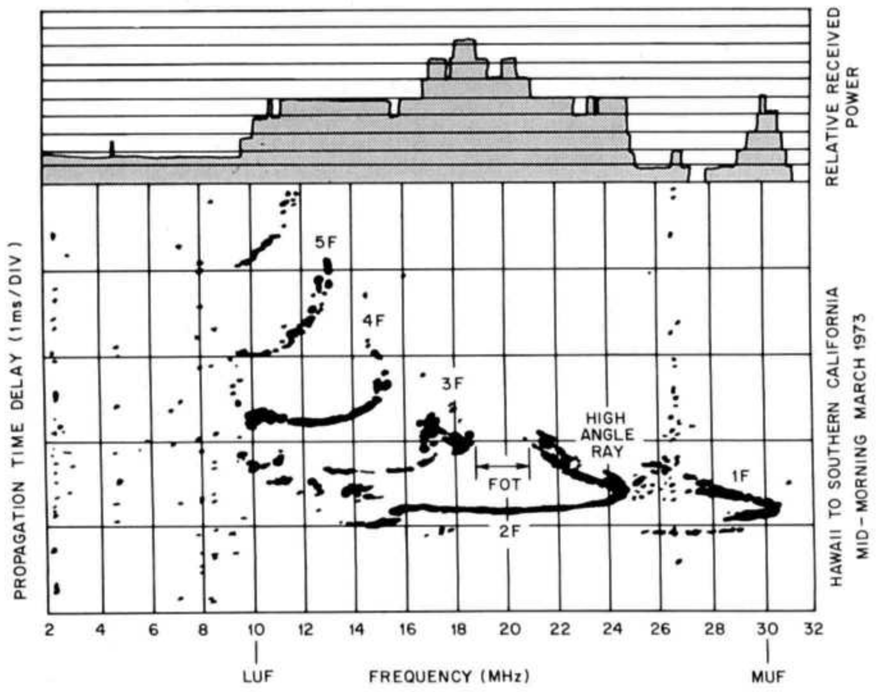

Fig 2—HF oblique sounder ionogram. This photo shows a typical chirpsounder measurement on a 2500-mile path during midmorning in March.

Let's first consider $T >> T_m$. When this condition is satisfied, the data signal tends to undergo flat fading (all signal components fade together). HF packet signals operating at 300 bit/s are susceptible to flat fading conditions when the multipath spread is less than 0.3 ms. The effect of flat fading on a data signal (whose signal-to-noise ratio [SNR] and bit-error rate are varying) is periods of relatively error-free copy, interspersed with dense bursts of errors when deeper fades occur. A number of techniques, such as diversity reception, can reduce the harmful effects of flat fading. Note that the condition stated for flat fading assumes that the bandwidth of the modulated data signal is similar to its baseband bandwidth. This excludes such schemes as spread-spectrum modulation and wide-shift FSK; in effect, these schemes already have a form of frequency diversity built into them.

When $T >> T_m$ is not satisfied, a selective fading situation occurs (not all signal components fade together). This condition is best viewed in the frequency domain. The effect is that of having passed a signal through a filter having one or more notches, and the center frequency, width, and depth of the notches all vary with time. Selective fading is common with voice signals; it causes noticeable distortion, but seldom seriously disrupts communications, especially in SSB emissions. There is redundancy in a voice signal, and the spectral notches and accompanying delay distortion are tolerable. Unfortunately, the effects of selective fading on data signals are not so benign.

The effect of selective fading on data signals is easier to visualize in the time domain. Consider that we are dealing with a multipath spread that is a significant percentage of the symbol length, say 10% or more. This means that for that percentage of a symbol duration (from the start of the symbol), energy is still arriving from the previous symbol. This phenomenon is known as *intersymbol interference*, or *ISI*. The greater the ISI, the more difficult it becomes to separate the transmitted symbols.

When the multipath spread exceeds about 10% of the symbol time, it becomes the dominant mechanism in controlling the bit-error rate. If the system is operating in this region, improving the SNR at the receiver (by increasing transmitter power or antenna gain) produces no significant improvement in error rate! In more technical terms, the bit-error rate is said to be *dispersion-limited* (as opposed to power-limited), or that the system is operating in a region of irreducible error rate. This situation should be avoided whenever possible. One straightforward solution is to reduce the symbol length. This leads to the variable-rate modem concept—if nothing is getting through at a given bit rate, reduce the bit rate until the error rate becomes tolerable. The symbol length can also be increased while maintaining the higher bit rate if some type of multilevel (nonbinary) signaling scheme is used. The tradeoff is that a higher SNR at the receiver is required for a given error rate. Although it cannot eliminate ISI, diversity reception can mitigate its effects by lowering the irreducible error rate to an acceptable value. Finally, the most exotic solution is to equalize the multipath channel with an adaptive equalizer at the receiver. These topics will be dealt with in later sections.

Fig 3 shows typical bit-error rate curves. The curves illustrate the dramatic effect that the presence of multipath-induced ISI has on an HF data link. One set of curves is for flat fading (no significant ISI), while the other set shows when serious ISI is present ($T_m > 0.1T$). Notice that the curves "bottom out" at a relatively high error rate in the second case. A noticeable improvement is evident when diversity reception techniques are used. This particular set of curves is for binary differential phase-shift keying modulation, and were generated by a computer for a specific HF channel model; they should not be taken as definitive. They are representative, however, of the performance you can expect from most HF data systems.

Let's look at our HF packet station operating at 300 bit/s once more. The region of ISI-limited bit-error rates is entered when the multipath spread exceeds 0.3 ms. Unfortunately, this occurs often, and the figure is frequently exceeded by a wide margin, rendering the link unusable.

Measured data on multipath spreads are not easy to come by, but I have made a number of observations on short-range paths (60-1000 km) in connection with HF data system tests. I estimate the average spread to be about 1 ms, with values of 3 or 4 ms not uncommon. Some data on longer-haul paths have been published.[6] For example, measurements taken over a four-year period on the 6000-km path between Washington, DC and London show an average multipath spread of about 1.3 ms. The observed spread was less than 1 ms for only 30% of the time, and it exceeded 3 ms for 5% of the total period. Similar observations on the 9600-km path between Tokyo and London yielded even higher values: An average spread of about 2.4 ms, less than 1 ms for only 5% of the time, and greater than 3 ms for a whopping 19% of the time!

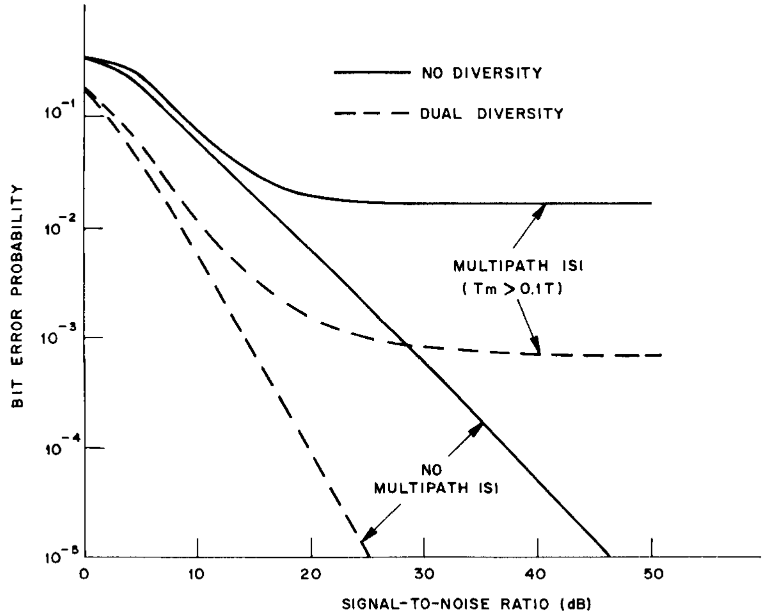

Fig 3—Effect of multipath propagation on bit-error rates.

In addition, there are other impairments that increase in severity with decreasing symbol time. One example is Doppler spreading, a phenomenon most prevalent on signals that traverse the auroral zones, resulting in the "Arctic flutter" effect. It has a limiting effect on achievable bit-error rates that is similar to that of multipath propagation. As bandwidth is increased to accommodate faster signaling rates, interference from other stations can also be expected to be more severe. The conclusion is clear: Whether the path is short or long, a conventional FSK modem running at 300 bit/s is not going to deliver a usable error rate for a significant proportion of the time that the band is open and providing an adequate signal level. During these times, increasing transmitter power or antenna gain will *not* help. It is nice to be able to run at 300 bit/s (or more) when the channel supports it, but be prepared to fall back to a lower rate, say 75 or 100 bit/s, when it does not. Better yet, the 300 bit/s modem should be designed to perform just as well as the lower-speed modem!

The nastiness of HF fading raises the question, are all nonamateur HF data systems restricted to very low data rates? In fact, the vast majority of them do operate at rates in the neighborhood of 100 bit/s. To go to a higher transmission rate, the required bandwidth increases, and the price of a suitable modem seems to rise exponentially with bit rate. HF modems are available for rates up to at least 2400 bit/s, but the majority of the customers are military, to whom cost is seldom an overriding concern! The increasing availability and decreasing cost of digital signal processing (DSP) components, however, should help to bring the techniques involved within reach of the amateur fraternity. The problem of limited bandwidth available in the amateur bands is a much more serious limitation, as higher data-rate signals occupy the equivalent of a voice channel. The relatively wideband emissions associated with the 1200-bit/s and higher-speed modems would not be welcome additions to the congested HF bands. In the long run, they should not be necessary as high-speed satellite and terrestrial links, and higher levels of networking to support them, become available. At the present time, efforts should focus on the design of a high-performance 300-bit/s modem.

Parallel Modems

Commercial HF modems operating at medium- and high-bit rates (300 bit/s and up) can be categorized as parallel or serial. Parallel modems simply multiplex the data stream into several low-speed subchannels. These subchannels are spaced far enough apart in frequency to avoid interfering with each other. A prominent (and costly) example is the modem defined in the military specification MIL-STD-188C. It uses 16 subchannels spaced 170 Hz apart, plus an additional tone for correction of tuning errors and Doppler shift. Each subchannel has a basic symbol length of 13.3 ms, which normally corresponds to a rate of 75 bit/s per subchannel; however, the modulation is four-phase PSK, and it allows two bits per symbol to be transmitted, for a total data rate of 2 × 75 × 16 = 2400 bit/s. In practice, this modem is often used in an in-band frequency diversity mode in which the same data bit is transmitted on two or more subchannels simultaneously. This ploy lowers the effective data rate, but increases the probability of demodulating the bit correctly (diversity reception is discussed next month).

Application of the parallel modem concept to a 300-bit/s design is straightforward. For example, consider the 100-bit/s rate recommended above for a single FSK channel. For this rate, the recommendations of the CCIR for frequency shift and spacing between adjacent channels are 80-85 Hz, and 170 Hz, respectively.[7] Thus, we might have three parallel 100-bit/s FSK subchannels with center frequencies of 425, 595, and 765 Hz (these happen to be the first three recommended center frequencies, but many other choices are possible). The three subchannels could be easily constructed from separate FSK "building blocks" similar in design to those used presently by amateurs. The inputs to the three subchannels would be derived from a 1-out-of-3 data multiplexer, and the three outputs summed before being applied to the transmitter. An attractive alternative would be to implement all three subchannels with a single DSP chip. A modem using one of these devices has the considerable advantage of needing no tuning whatsoever—it comes to life with all filters and oscillators perfectly tuned and stays that way! (Some analog filtering is needed for anti-aliasing and reconstruction in the analog-to-digital-to-analog conversion processes, but this is relatively noncritical and should never require adjustment.) The cost of DSP devices and their development tools has kept them out of amateur applications, but it is just a matter of time before they make their presence felt. DSP chips are the wave of the future in low-frequency signal processing.

Serial Modems

The second major modem category is the serial modem. One signal (normally a sinusoid modulated in frequency or phase) at a time is transmitted. Most telephone-type modems, and virtually all modems presently used by amateurs, fall into this category. Each signal (symbol) may represent a single bit of information, in which case the modulation technqiue is called binary (as in the 300-bit/s and 1200-bit/s binary FSK modems now used for AX.25 data links). In this case, the signal has two possible states, commonly called *mark* and *space*. Most 1200-bit/s and higher-rate modems produce signals with more than two states, and thus carry more than one bit of information per symbol; otherwise, their spectra would not fit within a standard voice channel. Serial modems tend to have much shorter symbol lengths than parallel modems operating at the same bit rate, and therefore, they require a more well-conditioned channel in order to avoid intersymbol interference. Most telephone-line modems include an equalizer to condition the channel. The equalizer consists of a filter in front of the modem that is designed to flatten the amplitude and time delay response of the channel and thereby reduce the intersymbol interference and other distortion that result in reduced noise margins in the demodulator. Some modems, such as the 212A 1200-bit/s type, use a fixed equalizer design based upon typical telephone channel characteristics. More sophisticated higher-speed modems use an adaptive strategy: At the beginning of the call, a special *training sequence* is transmitted from each end of the circuit to enable the receiving modem to adjust the parameters of its equalizer for minimum distortion of the received data signal.

The principle of adaptive equalization also applies to HF modems, but successful implementation is much more difficult. Since the response of the channel is now time-varying, the equalizer parameters must be updated frequently. This generally means that the training sequence must be periodically reinserted into the data stream to allow re-adaptation. Modems that use the training sequence technique are generally known as *reference-directed adaptive modems*. Other adaptation algorithms have been developed which do not require special sequences to be transmitted. For example, the equalizer can be adjusted to maximize the demodulator "eye pattern" opening without knowledge of the actual data sequence transmitted (Fig 4). This mode of operation is known as *decision-directed*, and is more desirable because of the lack of overhead involved. Since the mid-60s, a number of attempts have been made to implement adaptive serial HF modems, mainly for the 2400-bit/s data rate. These designs share a common characteristic: When a channel is reasonably well-behaved (eg, slow fading), they tend to perform well, sometimes even spectacularly. When the channel deteriorates, there is a point when the rate of adaptation is insufficient; the modem cannot keep up with the fluctuations in the channel, and it fails equally spectacularly. In the latter case, a parallel modem may still deliver a usable error rate and therefore work over a wider range of conditions. On the other hand, the serial modem may offer higher overall throughput by virtue of better performance during the majority of the time, when the channel is not varying too rapidly. One reason for this better performance is because the serial modem transmits a single sinusoid at a time, and thus produces a more or less "constant envelope" signal; contrast this with the parallel modem output, which is a summation of several sinusoids. The parallel modem signal therefore has a higher peak-to-average ratio, and consequently yields an output signal with lower average power from a typical peak power-limited transmitter (note that the clipping and compression techniques often used to overcome a similar problem with voice signals are not tolerated by data signals!). All things being equal, the serial modem has more "sock" to cut through the noise and QRM when these are the primary limitations to communicating on the channel. Considerable effort continues to be expended on adaptive serial designs, and their performance should continue to improve as the state of the art in DSP devices advances.

Although adaptive serial modems are

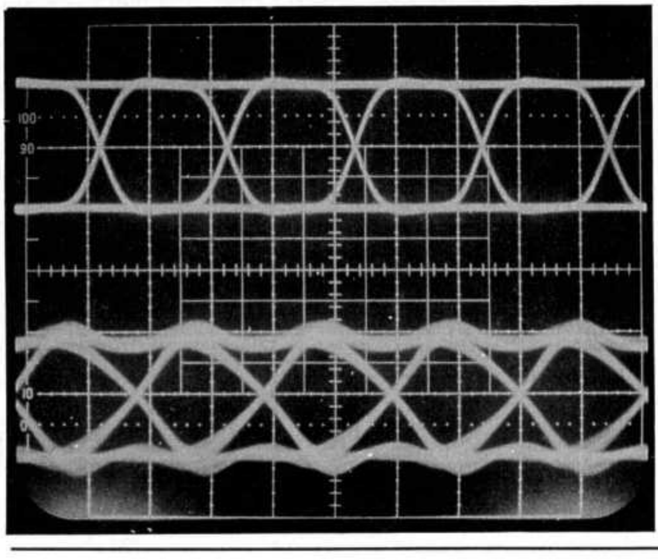

Fig 4—A typical modem eye pattern. The upper trace is the digital baseband signal before modulation. The lower trace is the received data after demodulation.

presently difficult and costly to design and build, they should eventually find their way into amateur applications. Making one work well at 300 bit/s might be considerably less difficult than at 2400 bit/s and higher. (Experimentation with higher data rates is largely a result of a strong military interest in secure digitized speech.) One intriguing possibility is the design of an adaptive equalizer to work with the presently-used 200-Hz shift 300-bit/s modems. Perhaps there is a well-heeled experimenter reading this who needs a challenge!

Variable-rate Modems

A useful concept that can be applied to both parallel and serial modems is that of the variable-rate modem. The basic idea is that the channel capacity (the maximum rate at which information can be reliably transmitted) of an HF link with a given bandwidth is not fixed, but time-varying. To keep the link reliable, the signaling rate should be adjusted to match the available capacity. In contrast to a fixed-rate modem, which is likely to collapse in the face of worsening conditions, the variable-rate modem allows the throughput to degrade gracefully. This concept is embodied in the Packet Adaptive Modem described by Rinaldo.[8] Perl describes a much more sophisticated design—a parallel modem utilizing DSP techniques to provide six possible rates from 75-2400 bits/s.[9]

Although simple in concept, the variable-rate modem is tricky to implement. The problem is developing a suitable algorithm to monitor system performance and carry out the necessary adaptation automatically. Performance monitoring is not too difficult, but any changes that ensue must be coordinated between the two ends of the link. This calls for a highly robust low-speed link piggybacked on the main data link. Such a link is often termed an *order wire*. Development of an effective variable-rate modem appears to be a worthwhile objective for the amateur community; in particular, a variable-rate serial adaptive modem would be less difficult to implement than a high-speed fixed-rate serial modem with adaptive equalizer, and it would avoid the peak-power limitations of the parallel modem.

HF Receiver Design

Some aspects of equipment design for data transmission, such as faster turnaround time, are being addressed by manufacturers of Amateur Radio gear. They may, however, be less than fully cognizant of the requirements imposed by packet-type modes of operation, particularly in the area of HF receiver design.

It is probably safe to say that the most important element of the HF receiver used for packet operation is the IF filter. Gustafsen made a comparative study of HF modems, and demonstrated that an audio filter, no matter how good, is not an adequate substitute for a suitably narrow IF filter.[10] The crucial difference is that the audio filter does not prevent unwanted signals outside its passband from reaching the AGC detector. This results in receiver desensitization and cross-modulation on the desired signal. The optimum IF filter bandwidth depends on the type of data signal being received. For the 300-bit/s, 200-Hz shift binary FSK emission in present use, a study done in the early 1970s indicates the optimum bandwidth should be about 360 Hz.[11] This is a bit narrower than Gustafsen's recommended range of 400 to 500 Hz.

One good reason to use a wider than optimum filter is that available IF filters tend to have severe delay distortion (nonlinear phase characteristics). This distortion is worst near the passband edges, and is a consequence of designing the filter for maximum possible rolloff rate in the stopband. The variation in delay over the filter passband can easily be several milliseconds; this can cause considerable ISI and higher error rates in the data signal. A suitable equalizer can reduce this distortion, but may be unnecessary as filters with characteristics more suited to data transmission become commonly available.

Another aspect of HF receiver design is optimization of the AGC system for packet transmissions. There is little doubt that the slow-release type of AGC time constant used for SSB reception is not suitable for data reception, especially during times of severe atmospheric noise. It is not clear, however, that the faster AGC characteristic commonly used for CW reception is always the best choice. In any case, the "optimum" is likely to be dependent on band conditions. Several speakers delivering papers at a 1985 HF communications conference mentioned the dearth of knowledge concerning optimization of receiver AGC for data transmission. One stated that better results were achieved by disabling the AGC entirely and carefully setting the RF gain manually.

Next month, we'll look at diversity reception and how it applies to packet-type data communications. Also, we'll examine several other types of signal processing (soft-decision decoding and hybrid ARQ) that can help to improve throughput on the HF channel.

Notes

[1] Robert C. Sommer, "A note upon another error detecting code that is not proper," *IEEE Trans Communications*, Jul 1985, Vol COM-33, No. 7, pp 719-721.

[2] Jerome T. Dijak, "AMTOR, AX.25, and HERMES: a performance analysis of three systems," *Ham Radio*, Dec 1985, pp 63-74.

[3] T. Fujiwara, et al, "On the undetected error probability for shortened Hamming codes," *IEEE Trans Communications*, Jun 1985, Vol COM-33, No. 6, pp 570-574.

[4] G. D. Forney, Jr, "Burst-correcting codes for the classic bursty channel," *IEEE Trans Communications Technology*, Oct 1971, Vol COM-19, No. 5, pp 772-781.

[5] Kenneth Davies, *Ionospheric Radio Propagation*, National Bureau of Standards Monograph 80, Apr 1965, p 295.

[6] CCIR, Report 203-1, "Path time-delays and shifts caused by multipath propagation on radio circuits," *CCIR Green Book*, Vol 3, Geneva, 1982.

[7] CCIR, Recommendation 436-2, "Arrangement of voice-frequency telegraph channels working at a modulation rate of about 100 bauds over HF radio circuits," *CCIR Green Book*, Vol 3, Geneva, 1982.

[8] Paul Rinaldo, "Introducing the Packet Adaptive Modem (PAM)," *Second ARRL Amateur Radio Computer Networking Conference*, Mar 19, 1983, pp 2.71-2.74.

[9] J. M. Perl, "Channel coding in a self-optimizing HF modem," *Proceedings of the 1984 International Zurich Seminar on Digital Communications*, Zurich, Mar 6-8, 1984, pp 101-106.

[10] Eric Gustafsen, "HF Modem Performance Comparisons," *Packet Radio Magazine*, Vol 2, nos. 1 & 2, Jan-Feb 1987, pp 21-24.

[11] R. T. Bobolin and J. C. Lindenlaub, "Distortion Analysis of Binary FSK," *IEEE Trans Communications Technology*, Vol COM-19, Aug 1971, pp 478-486.

Feedback

An erroneous sentence appears in the article, "Optimum Wire Size for RF Coils," (Aug 1987 *QEX*). On page 7, second paragraph of the second column, the third sentence is in error. The author researched this area further to learn that the conductivity of hard-drawn copper wire is 97% of that of soft-drawn copper wire. The difference in RF conductivity, then, is in the vicinity of 1.5%, a negligible difference.

Correct Your Schematic

Andre Kesteloot, N4ICK, author of "Extracting Stable Clock Signals From AM Broadcast Carriers for Amateur Spread-spectrum Applications," (Oct 1987 *QEX*, p 5), notes two things missing from Fig 3 on p 6: U1 should be labeled ECG 1292, and insert a 560-pF mica capacitor between the wiper of R1 and the junction of the 220-kΩ resistor and the base of Q6.

Far-Field Fallacy

**By H. Paul Shuch, N6TX
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If you've ever attended a regional VHF or UHF conference that featured antenna-gain measurements, you've no doubt heard the arguments. "The range was too short," a disgruntled contestant laments. "My antenna didn't give a good account for itself because it was in the near field. I *know* it has more gain that that!" And as much as it sounds like sour grapes, he may have a point. Put simply, the performance of DX antennas needs to be measured under DX conditions. But why, exactly, is there a near-field restriction? And how can we know how far afield is far enough? Immediately following the 1987 West Coast VHF/UHF Conference (where my antenna didn't do as well as I *know* it should have), I set out on a quest of discovery. Here is what I found.

The Traditional Explanation

Short electromagnetic waves travel through free space in straight lines, and antennas know this (even if antenna designers don't). Try as we might, we can't really direct electromagnetic radiation in a pencil-thin beam: The wavefront ahead of a radiating antenna spreads out with distance. Visualize the expanding radiation pattern, as shown in Fig 1, and you will see why antennas have a definable beamwidth.

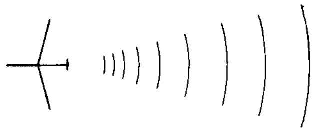

Fig 1—Visualizing the beamwidth for a radiating antenna.

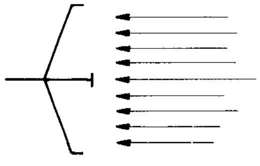

Fig 2—Planar wavefront arriving at a receiving antenna.

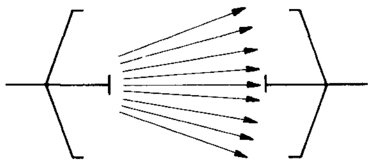

Fig 3—The near-field problem occurs because a nonplanar wave front appears at the receiving antenna.

To intercept the greatest amount of incoming energy, we design our receiving antennas to capture as much of the spreading beam as possible. This is normally accomplished by making antennas physically large, although a number of techniques exist for increasing the capture area of an antenna (that is, making it electrically large, even though it is physically small). We increase antenna gain by intercepting as many of the rays of radiated energy as possible—see Fig 2.

The problem is this: To function efficiently, the receiving antenna needs to intercept a planar wavefront. That is, the individual rays need to be arriving in parallel. If the distance between the transmitting and receiving antennas is great, this is very nearly the case. If the physical size (or capture area) of the receiving antenna is great relative to its distance from the energy source, however, a problem occurs. As Fig 3 shows, the received energy arrives as nonparallel rays that basically reach the receiving antenna out of phase with each other, and partially cancel. Hence the gain of antennas measured in the "near field" (where the received energy is not a planar wavefront) will be in error.

The Analytical Approach

The engineering textbooks describe the field in front of a radiating antenna as being divided into three distinct regions: a Fresnel zone, or near field; a Fraunhofer zone, or far field; and a transition zone. The significance of these three regions to antenna measurements is as follows: The power collected by a receiving antenna within the transmitting antenna's near field is very nearly constant, varying perhaps ±2 dB about a mean value with changes in distance. When antenna spacing is increased to far-field distances, recovered power will vary inversely with the square of distance. Within the transition zone, neither constant power nor the inverse square law holds.

The near-field region produces maximum power density at a fixed distance, which can be readily predicted:

$$d = \frac{0.2\ D^2}{\lambda} \qquad \text{(Eq 1)}$$

where

d = the distance from the radiating antenna at which maximum power density occurs
D = the diameter of the antenna (assuming a parabolic reflector)
λ = the operating wavelength

All three dimensions are expressed in like units. For a parabolic reflector antenna, the near field extends outward for a distance approximately equal to

$$d = \frac{\pi\ D^2}{8\lambda} \qquad \text{(Eq 2)}$$

where d now represents the near-field boundary, and the other literals are as defined above.

The distance d to the beginning of the far-field region is approximated by:

$$d = \frac{2\ D^2}{\lambda} \qquad \text{(Eq 3)}$$

with d now representing the far-field boundary, and all other factors are as defined above. Note that the far-field boundary is a factor of (16/π), or 5, times as far from the antenna as the near-field boundary. The region between near and far fields is considered the transition zone.

For antenna gain measurements, it is desirable for the receiving antenna to be in the far field of the transmitting antenna, and vice versa. Eq 3 thus becomes the most significant of the above relationships for our purposes. Note that the far-field boundary varies directly with the *square* of antenna diameter, and inversely with wavelength. Thus for physically large antennas operated at high frequencies (a situation frequently encountered by microwave hams), the required path distance for antenna measurements can become quite great.

A Philosophical Objection

The problem with the above equations is that they tend to obscure the physical mechanism that we are trying to study. Being able to predict mathematically the distances defining the near-field and far-field boundaries is a far cry from visualizing exactly *why* these distances make a difference in antenna measurements. If we desire to emphasize concepts rather than computations, we're going to have to come up with an explanation, perhaps invoking mechanical analogies, of exactly *why* all this matters.

That's where I got stumped. The equations were just too complex, and the fudge-factors too arbitrary, to point to an obvious relationship. Furthermore, no amount of research led me to an explanation of what physical constraints led to the boundaries being exactly where the equations say they are. I found in the literature an extensive body of knowledge on near- and far-field considerations, but no one bothered to go beyond the math. The numbers were considered sufficient unto themselves.

Well, not for me. Being perhaps more philosophical than technological, I consider the universe to be an orderly place, with all physical laws ultimately knowable and inherently simple. If it takes a complex set of equations to describe a phenomenon, I contend, it's only because we don't yet fully comprehend it. Once a relationship is fully understood, it becomes intuitively obvious, no longer requiring justifying mathematics. This is the level of understanding that we generally describe as inspiration, that gives rise to sudden exclamations of "Aha!" Unfortunately, as I contemplated antenna measurements near and far, no such inspiration presented itself.

Let Logic Prevail!

The only thing more mysterious than the workings of antennas is the workings of the human mind. I had pretty much put the whole dilemma out of my consciousness for about two weeks, when inspiration hit me over the head like a falling section of Rohn 25. Early one morning from a sound sleep, I literally awoke with a start, and said out loud "Aha! So *that's* why!" My wife Suk, WA6PLF, who after nearly twenty years is accustomed to such outbursts, got up to make coffee. I sat down at the word processor and attempted to document what was suddenly, inexplicably, intuitively obvious. I wondered, as I so often have, "Why didn't I see it before?" Here is the thought process that led to that revelation:

Consider two ideal, lossless, perfectly matched isotropic antennas, one radiating, the other receiving. Let's separate these from each other in free space by a distance of, say, 25 wavelengths at the operating frequency. (I chose 25 wavelengths because this distance corresponds to exactly 50 dB of isotropic free-space path loss.) If we apply exactly 1 W of RF to the transmitting antenna, the power recovered by the receiving antenna will be just 50 dB less, or 10 μW. This makes a calibrated path for antenna gain measurement.

Now replace the isotropic antennas with two identical gain antennas, one at each end of the path. Assume that the power collected by the receiving antenna is accurately measured at 10 mW. This is exactly 30 dB more than the signal power received when both antennas were isotropic, which leads us to the conclusion that, between them, the antennas had 30 dB of gain. Since the two antennas are identical, each has a gain of +15 dBi.

So far we have simply described a standard measurement of antenna gain employing the power ratio method. The technique is an accepted method of calibrating standard-gain horns. It doesn't require that we actually perform a measurement between isotropic antennas (which we can't really build, buy, or find in nature anyway), because isotropic free-space path loss is readily calculable.

We can continue the above process by replacing the two 15-dB-gain test antennas with two more antennas, still identical, each producing a gain of, say, +20 dBi. The total antenna gain is now +40 dB, and the path loss is unchanged, at 50 dB. Our received signal power can thus be expected to be a total of 10 dB weaker than that transmitted, or 100 mW. Power ratio measurements should still be valid.

Now comes the interesting part. Let's increase the size (and hence gain) of our two identical antennas once more, to an assumed gain of +30 dBi each. Total path loss is still 50 dB. Total antenna gain is +60 dBi. Therefore, the power received is going to equal 10 dB more than the power transmitted, or 10 W. Right?

"Wait a minute," you say. "That's impossible!"

Aha!

Clearly, the received power cannot exceed that transmitted; that would violate the principle of conservation of energy. This means that, as we continue to increase antenna gain, we reach a point where the received power can't continue to increase. For the wavelength at which we're operating, at the distance we've selected, with the antennas we're trying to measure, we have just entered the twilight zone—er—near field.

This happened just where the combined gain of the two antennas *exactly* equaled the free-space isotropic path loss between them. Of course, the same analysis could have been made by holding the size (hence gain) of the two antennas constant and decreasing distance (hence free-space path loss) between them. We would still have reached a point where recovered power could no longer increase. Is the mechanism becoming clear?

Good engineering practice suggests that, whether we're increasing antenna gain or decreasing distance, we should stop several decibels *before* we run out of available received power—which suggests to us roughly where the far field should start. All of this leads to the following conclusion: "To accurately measure antenna gain, the distance between transmitting and receiving antennas must be sufficient to produce a free-space isotropic path loss that *significantly exceeds* the total gain of the receiving and transmitting antennas."

Okay, how much additional path loss is "significant"? By comparing Eqs 2 and 3, we determined that the far field starts five times as far from the antenna as the near field ends. The difference in free-space isotropic path loss for a distance factor of five is: $10 \log (5)^2 = 14$ dB. Thus, to be at the far-field boundary, we need to make the free-space isotropic path loss at least 14 dB greater than the combined gain of the two antennas involved.

This would place us right at the far-field boundary. For good measure, let's restrict ourselves to operating well within the far field, by doubling the minimum distance. Doing so adds exactly 6 dB of additional path loss (remember, twice the distance is half the recovered voltage, or a quarter of the recovered power, or 6 dB less signal). As a practical guideline, then, the path loss should be at least 20 dB greater than the combined gain of the two antennas.

As an example of how this guideline might be used to determine the required length of an antenna range, let's consider a 10 ft dish at 1296 MHz (expected gain: +30 dBi). Let the antenna at the other end of the range be a standard-gain horn (expected gain: +15 dBi). The minimum range length is that which exhibits significantly more than 45 dB of free-space path loss.

Our guidelines suggest that a −65 dB path is acceptable. This translates to a distance of 32.5 meters, or 106 feet. If the length of the range at last year's Conference was shorter than this, and your 10-ft dish didn't measure up to your expectations, you may have a valid gripe.

On the other hand, maybe for no good reason, your dish just doesn't have as much gain as the equations say it should. Antennas are like that, you know.

The Morphological Table—An Invention Generator

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This paper presents a technique for producing concepts that can be developed into actual inventions. The technique is easy to use, and ideal for generating new ideas in communications and electronics technology.

Generating Ideas

There are numerous opportunities for developing new inventions. You can encourage your own creative efforts by using what is called a *morphological table.* This table was developed by "think tank" organizations to stir up new ideas.

A morphological table, like that shown in Table 1, consists of sets of words. The X-axis of the table has a word at each position along the axis. Note that each word is related to every other word on the X-axis. In this example, the words are the names of materials such as water, copper, oxygen, and so on.

The Y-axis of the table also has a word at each position along the axis. These Y-axis words are related to each other, and in this example the names are of components such as capacitors, resistors, inductors, and the like.

The table works this way. Each cell of your morphological table joins one X-axis word with one Y-axis word. For example, one cell contains "water-capacitor" and another cell has "oxygen-inductor." Thus, each cell of the table suggests a possibility such as a capacitor made out of water!

Most of these possibilities are silly, of course, and some are physically impossible. Others, however, may be the seeds of new inventions such as capacitors made out of water. It is up to you to filter out the useful ideas from all of the combinations displayed by the table.

You can use the morphological table to show all the combinations of any two sets of words. Since the table is a simple mechanism, it generates possibilities that are different from the conventional ways of doing things. This technique works best if you have many words on each axis. The result is a lot of cells and a lot of displayed possibilities.

Table 1
The Morphological Table

	Water	*Copper*	*Oxygen*	*Sulfuric Acid*
Antenna	Water-Antenna	Copper-Antenna	Oxygen-Antenna	Sulfuric Acid-Antenna
Capacitor	Water-Capacitor	Copper-Capacitor	Oxygen-Capacitor	Sulfuric Acid-Capacitor
Inductor	Water-Inductor	Copper-Inductor	Oxygen-Inductor	Sulfuric Acid-Inductor
Resistor	Water-Resistor	Copper-Resistor	Oxygen-Resistor	Sulfuric Acid-Resistor

Table 2
Compute Your Own Morphological Table

```
10    CLEAR 4000
20    PRINT "ENTER NO. OF WORDS
         ON EACH AXIS"
30    INPUT Q
40    FOR N=1 TO Q
50    PRINT "INPUT X WORD", N
60    INPUT A$(N)
70    NEXT N
80    FOR Z=1 TO Q
90    PRINT "INPUT Y WORD", Z
100   INPUT B$(Z)
110   NEXT Z
120   REM OUTPUT SECTION
130   FOR N=1 TO Q
140   FOR Z=1 TO Q
150   LPRINT A$(N), B$(Z)
160   NEXT Z
170   NEXT N
180   END
```

Computerized Morphological Tables

It is easy to create an automated morphological table. Simply nest one loop within another to generate your morphological table. The BASIC program listed in Table 2 can generate large tables.

This program allows you to enter two lists of words using for-next loops (lines 40 through 110). The range (number of words in each list) of the loops is entered by line 30.

The program's output section uses nested for-next loops to print out pairs of words (lines 120 through 170). First, the second list is paired with the first word from the first list. Then, the second list is paired with the second word. This process continues until the entire table of possibilities is printed out.

Additional Steps

The next steps in inventing are up to you. The process of attempting to develop a new invention is interesting, enjoyable, and educational. In addition, inventing offers an opportunity to contribute to the development of communications. Remember that there is more than one way to generate, modulate, and detect radio waves!

Bits

Surplus Modules for the IBM PC

Surplus IBM data acquisition modules suitable for use with the IBM PC and ideal for automatic antenna rotator applications are being offered for sale by a Dayton, OH company. According to John Biro, K1KSY, the units are available from Mendelsohn Electronics, Inc, for $195 + $6.50 shipping. The units come with a sample Turbo Pascal driver and they offer an advanced Turbo disk. John found that the sample disk included enough information to program the unit so the advanced disk was not needed. For information you should call the company at 513-461-3525. *Tnx Amateur Satellite Report*

AMSAT-NA Technical Journal Available

Twice a year, AMSAT-NA gathers technical papers that detail original work in the space communications area and related fields. Reports of significant findings in the fields of low-cost satellite design, construction, operation, and space sciences are featured in these works that are later published in the *AMSAT-NA Technical Journal.* The Summer 1987 volume contains articles by Amateur Radio operators who are also engineers dedicated to broadening the space communications horizon.

Articles include information on RUDAK, UoSAT-2 and tracking algorithms. Cost of this publication is $10. For further information about the *AMSAT-NA Technical Journal* and AMSAT membership benefits, write *AMSAT-NA Technical Journal*, AMSAT, 850 Sligo Ave, Suite 601, Silver Spring, MD 20910.

Improved Satellite Tracking Program

The new version of the satellite tracking program, Quiktrak 3.1, has been fully tested. Some of the new functions include showing the sun's position by an on-screen cross-hair indicator, and displaying all the satellites at once. The software supports the Hercules card via SIMCGA, and fully tested with the KLM/ARRL controller. For ordering information on Quiktrack 3.1, contact Robert McGwier, N4HY, 917 McKinley Ave, Auburn, AL 36830.

FCC Experimental Action

KA2KDY, Teledyne Ryan Aeronautical Co, Airborne. Granted CP and License for new station to operate in restricted airspace near Los Angeles, CA. Frequencies of operation are 908 and 922 MHz, to provide communication for research project.—*Excerpted from an FCC Public Notice, Report No. 231, Oct 7, 1987*

The Commodore Diagnostician

If you are a C64 user, you should know about the Commodore Diagnostician. This chart was developed in Australia in 1986, and used successfully to diagnose and find faulty chips on the C64 and peripherals. The chart features 80 symptoms and possible solutions. A pictorial of the C64 chip layout is included with corresponding identification numbers. Chart cost is $6.95 plus $1 shipping and handling. An IBM Diagnostician is due out soon. Contact Kasara Microsystems, Inc, 33 Murray Hill Dr, Spring Valley, NY 10977, tel 914-356-3131, outside NY 1-800-642-7634 or 1-800-248-2983.

Improve the Sensitivity of Your Test Equipment

The RFSP Signal Intensifier™ is both a high-performance receiver and instrumentation amplifier that provides super high gain and wide bandwidth amplification. The unit is housed in an aluminum enclosure, and comes complete with a self-contained 120-V ac power supply. The Intensifier covers 50-1000 MHz, and has a gain of 20 dB and a noise figure of 3 dB. BNC connectors provide for input and output connections. Price: $69.95.

A second unit, called the RFX, is designed for inclusion inside existing receivers, transceivers, scanners, or instrumentation. The RFX provides a gain of 13 dB with a noise figure of less than 5 dB. Frequency coverage is from 20-1000 MHz, and each small unit (4.3 cm × 3 cm × 2.5 cm) is powered by 10 to 18 V dc. A one-foot length of RG174 coaxial cable is included for RF input and output connections. Price: $24.95. Contact Electron Processing, Inc, PO Box 708, Medford, NY 11763, tel 516-764-9798.

ENCOMM Inc Appointed New Distributor for Yaesu Rotator Products

Yaesu has chosen ENCOMM, Inc to be their US distributor of antenna rotator products. Yaesu has recently acquired the largest antenna rotator manufacturing facility in Japan, and plans to pass along their fine-quality products to the US through ENCOMM. For further information, contact ENCOMM, Inc, 1506 Capital Ave, Plano, TX 75074, tel 214-423-2204.

New Mouser Catalog

A free 176-page catalog is now available from Mouser Electronics. Stocked with over 16,000 items, it serves as an excellent guide for the experimenter or anyone needing quick access to up-to-date product data. Contact Mouser Electronics, 2401 Highway 287 North, Mansfield, TX 76063, tel 1-800-992-9943, in TX 817-483-4422.

>50

Focus on technology above 50 MHz

By Bill Olson, W3HQT
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Troy, ME 04987

VHFers' Guide to Continuing Education

This month I'm going to take a break from technical talk and discuss other places where you can find out the latest information of interest to VHF/UHF/microwave experimenters. We are a small community, and we have a very tight-knit support organization. The network for sharing ideas and coordinating operating events is excellent, and anyone seriously interested in getting on the bands above 50 MHz should try to take advantage of this vast pool of information and knowledge. Once you get tied into any part of the network, everything falls into place.

Publications

There are several basic information sources that the VHF gang relies on. If you don't already have them, you should check out the VHF manuals. These include appropriate sections of *The ARRL Handbook* and *The ARRL Antenna Book*, the RSGB *VHF/UHF Manual* and the *UHF Compendiums* from West Germany. Articles and columns in the mainstream magazines—*QST*, *QEX*, *CQ*, *Ham Radio* and *73*—are all of interest, as well as the West German *VHF Communications* and the RSGB journal, *Radio Communications*.

A great resource is the monthly newsletters dedicated solely to operation on VHF and above. While the circulation of these newsletters is small, they are full of information just for the VHFer. Some newsletters I know of are listed here. I'm sure there are others. If you know of some I've missed, let me know so I can pass the information along.

VHF/UHF and Above Information Exchange, c/o Rusty Landes, KA0HPK, PO Box 270, W Terre Haute, IN 47885

KC0W's VHF-Plus Update, 4016 Narrows Rd, Erlanger, KY 41018

Midwest VHF Report, 3451 Dudley St, Lincoln, NE 68503-2034

The Rochester VHF Group Journal, c/o Thomas Hodge, WA2YTM, 6484 Rt 96, Victor, NY 14564

Pack Rats *Cheese Bits*, c/o Harry Stein, W3CL, 2087 Parkdale Ave, Glenside, PA 19038

DUBUS, c/o Rusty Landes, KA0HPK, PO Box 270, W Terre Haute, IN 47885

Northeast VHF Association Newsletter, c/o Lew Collins, W1GXT, 10 Marshall Terrace, Wayland, MA 01778

The monthly newsletters have a much shorter lead time than the magazines, so the information is much more timely. In the columns in the major magazines, we normally hear about great summer band openings after the snow starts to fly (in Maine, anyway). Newsletters are the best place to learn of operating events such as grid expeditions, contest efforts and so on. They also contain technical information that is not in (and will probably never be in) the form required for publication in one of the "big" magazines. *VHF/UHF and Above Information Exchange* features a Skeds Wanted listing that is useful for those hunting rare grids or states—or just hunting.

The Pack Rats *Cheese Bits* and *The Rochester VHF Group Journal* are newsletters published by VHF clubs; they contain excellent operating and technical information. If you live in the area of one of these clubs, stop by a meeting sometime. You're sure to find someone to help you get started or help with technical problems.

Five Dream Vacations for the VHF/UHF Experimenter

If you've never attended one, make it a point to go to one of the yearly VHF conferences held throughout the country. The five major events are the Eastern VHF/UHF Conference held each May in southern New Hampshire; the West Coast VHF/UHF Conference held each May in California; the Central States VHF/UHF Conference held somewhere in the midwest in late July; Microwave Update held in Colorado around Labor Day; and the Mid-Atlantic States VHF/UHF Conference held in the Philadelphia area in early October. In addition, the East Coast VHF Society has recently revived its Antenna Measuring Contest at Trenton State University (NJ) in August. The Dayton HamVention® in April has often sponsored a VHF Conference; at the very least, Dayton is an informal gathering place for the VHF clan.

ARRL has started publishing Proceedings from three of the VHF Conferences: Central States, Microwave Update and Mid-Atlantic States. These proceedings are available through the League. It used to be that if you were *really* lucky, you could get someone who attended a conference to run off a copy of the proceedings. This is a lot of work—just barely worth the IOU incurred to return the favor!

The technical papers are just part of the conferences, though. If you attend in person, you get to ask questions, and the author/speaker can go into more detail. You'll probably even get a chance to look at and fondle a piece of real-live homebrew VHF equipment if you're so inclined. In addition to technical talks, there are often informal band sessions dedicated to operating on your favorite band or bands.

Then there are the flea markets—often small, but you won't have to maneuver past old radioteletype machines to get to the chip capacitors. The Pack Rats sponsor a huge flea market the day after the Mid-Atlantic States Conference. Occasionally you'll get a real treat: This year, the Central States Conference sponsors conducted tours of the local surplus emporiums. . . there were *many* full trunks and suitcases leaving Texas last July.

Conferences are a great place to socialize as well. Most include a family program, a banquet and a chance to sit and chat with someone who may usually be just a "ROGER S-2" at the other end of a meteor-scatter path! There is a VHF Conference near you sometime this coming year—*try it!*

VHF conference locations and dates are published well in advance, so keep an eye on the VHF columns in the magazines. I guess that means here too! The 1988 Central States VHF Conference will be held July 21-24 at the Villager Motel in Lincoln, Nebraska. Contact Roger Cox, WB0DGF, for information. That's the only one that I know definitely so far—but stay tuned.

A Final Thought

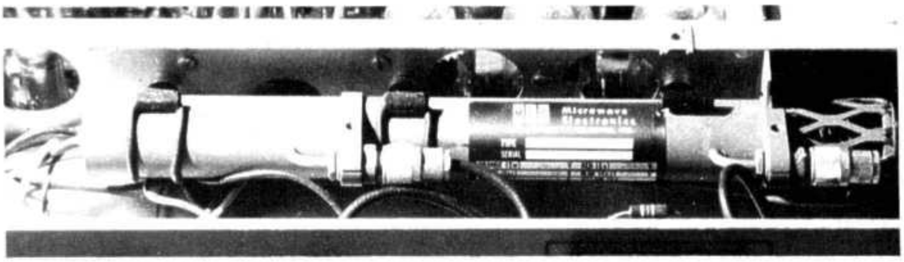
Oh yes, I almost forgot. . . Another excellent way to get information is to actually *get on the air!* It doesn't take long to find someone who is willing to help with a problem or point you in the right direction!

Next month back to class again. Thanks to everyone who has written and said kind words about my *QEX* columns—it helps!

VHF$^+$ Technology

By Geoff Krauss, WA2GFP
16 Riviera Drive
Latham, NY 12110

Traveling Wave Tubes



A close-up view of a TWT. Photographer Bob Atkins, KA1GT, is looking for circuit diagrams on both the Alfred 528 X-band TWT, and the E-R Research Labs Model 514 X-band TWT. If you can help Bob, write him at 103 Division Ave, Millington, NJ 07946. ***(photo courtesy of KA1GT)***

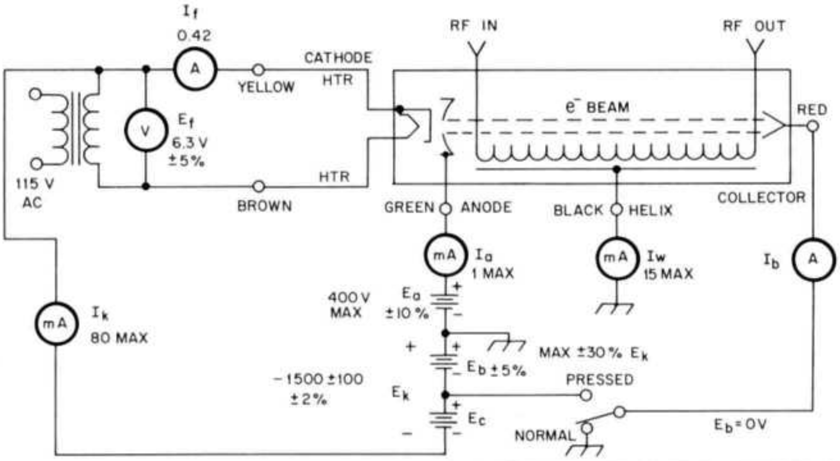


Fig 1—A 10-W traveling wave tube. Values are for the Hughes 564HD 2-4 GHz tube with a gain > 30 dB.

In a previous column (Sep 1986 *QEX*, p 16), I had asked for information on the 564HD traveling wave tube (TWT). A number of readers responded with the required data and/or data sheets. I extend a greatful *thank you* to them from myself, and those I've passed the data on to. At the same time, several puzzled readers asked what is a TWT and why does it appear to be so important to VHF + ers?

Without going into the history of UHF and microwave signal power generation, it is sufficient to state that all of the first amateur EME QSOs on any band above 2 GHz were achieved by stations using a TWT as the transmitter power amplifier. (If you include the klystron amplifier, a close relative of the TWT, it is all bands above 1 GHz.) Almost all high-power signal generation on the 2.3 + GHz bands today is produced by TWTs!

The cathode-grid-anode structure of the TWT is necessary to create and control electron flow. Unlike most power tubes used for lower frequencies, the TWT's annular anode does not capture all of the electrons it attracts. Many of these electrons stream through the anode aperture and form a beam that is attracted to at least one collector electrode at the opposite end of the tube. Typically, an array of magnets is used to focus the beam as it travels down the tube. These magnets can be electrically energized in higher powered TWTs, or they can be a set of periodically-placed permanent magnets (PPMs). Because a separate high-current magnet power supply is not needed, the latter is preferable for amateur use.

The other portion of the tube is the RF structure. This part consists of a conductive helix that surrounds the beam for most of its length, some form of launcher for coupling the incoming RF signal to the end of the helix near to the beam-forming electron "gun," and some form of catcher at the far end of the helix for coupling the amplified signal to the TWT output. The TWT operates by modulating the velocity of the electrons in the beam that travels down the center of the tube. The incoming RF signal is coupled to the beam in the launcher, causing the beam of electrons to bunch together. Some hairy math describes how the electrons are accelerated for instantaneous signal amplitudes of one polarity, and decelerated for instantaneous signal amplitudes of the other. It is sufficient to say here, however, that given enough length of beam along which the RF signal in the helix can continue to increase electron bunching in the beam, the greater the power in the bunches. The bunches clump with a spacing which is dictated by the input signal. The output signal, in a properly designed tube, is a faithful linearly amplified copy of the input signal—it has the same frequency, phase and amplitude characteristics, but much more power. TWT with gains in the 30-60 dB range are commonplace, as are output power levels of 0.1 W (+ 20 dBm) to 20 W (+ 43 dBm). Cost of a new tube is astronomical (in the $1000 + range); the cost of used tubes vary. Even more difficult to obtain is a complete TWT amplifier (TWTA).

The TWTA

A TWTA is a commercially-packaged TWT that includes associated power supplies and auxiliary equipment. It is not the TWTA's cooling technique or the fact that it provides RF connections to the TWT that make it so much more desirable than the bare TWT; most tubes useful for amateur applications are conduction or forced-air cooled, and have normal coaxial or waveguide RF connections. The power supply requirements are difficult to satisfy. Often, the beam collector and helix structures must be operated at ground potential, with the gun cathode set at a relatively high negative voltage. The gun grid may be at, or below, cathode potential, while the gun anode is often at a medium negative voltage (see Fig 1). Higher power TWTs require more voltage and current (I have a 1-kW, 2-4 GHz TWT that needs -7650 V dc at 1.8 A—guess how often I've come across a transformer for that supply!).

The most difficult requirement to meet is the over-current protection for the very delicate helix conductor. If the helix current exceeds some value, it is necessary that at least one of the power supplies (often the anode supply) be shut down in typically under 10 ms. Failure to properly protect the helix conductor will result in a damaged tube. There is often no separate helix current line; the current must be computed by measurement of at least one other current! A protection circuit that operates satisfactorily for one type of TWT may be fatal to another, even if it is from the same manufacturer. It is always desirable to have a copy of the TWTA manual on hand for your tube type.

Operating Manual Scarcity

TWT/TWTA manuals and data sheets are not easily acquired. Many of the tubes now available to amateurs were made more than twenty years ago. Because of these informational problems, I will attempt to keep a record/copy of as many tube types as possible, and act as an information exchange. I presently have TWTA manuals from ALTOS Research, data for many of the Keltec TWTAs, TWTs from ITT, and from Hughes (the 9xx series). If you need information, send me your TWT or TWTA type on a QSL; I will forward information when available (we can worry about postal costs then, hi). Be aware that I may never have anything to send, because of insufficient data. If you have access to TWT data or TWTA manuals, I'd like to copy the material for my files. I am especially interested in the manual or schematic for the Hughes Aircraft TWTA type 1177Hxx, specifically the 1177H01F that uses the illustrated TWT. (I have access to such a unit at work, but the manual is long gone and the Instrument Pool will not let me take it apart and "research" the supply/protect portion!)

Bits

Coil Sample Kits

For $39 you can buy one of three molded-coil sample kits. The first kit contains 123 parts, spanning 82 values, with frequencies of 30 to 150 MHz, and inductances of 0.0393 to 1.173 μH. The 7-mm sample kit contains 108 parts, with a span of 54 values. Frequencies range from 70 kHz to 50 MHz, and inductances from 0.1 to 220 mH. The 10-mm sample kit contains 136 parts, covering 68 values. Frequencies range from 79 kHz to 75 MHz, and inductances from 0.08 μH to 56 mH. Contact Toko America, Inc, 1250 Feehanville Dr, Mt Prospect, IL 60056, tel 312-297-0070.—*Tnx David T. Kjellquist, WB5NHL*

Books for Continuing Education

At last, a guide to the regulatory and technical aspects of the geostationary satellite orbit for satellite communications. Titled *Communication Satellites in the Geostationary Orbit*, authors Donald M. Jansky and Michel C. Jeruchim have combined two of the most important facets of this subject—a fully revised 1987 regulatory update, and a detailed engineering design and analysis review. This book is available for $60 from Artech House, 685 Canton St, Norwood, MA 02062, tel 1-800-225-9977, or in MA call 617-769-9750. Ask for ext 4002.

Intel has created handbooks for computer professionals, design and reliability engineers, as well as teachers and students of computer electronics and programming. The books are written to help those working with Intel products work more effectively. For a brochure of available handbooks from Intel write to Intel Literature Sales, PO Box 58130, Santa Clara, CA 95052-8130, tel 1-800-548-4725.

Howard W. Sams & Co is offering the *Handbook for Sound Engineers: The New Audio Cyclopedia*. Thirteen audio professionals wrote this comprehensive reference book. All aspects of audio technology are discussed, including the most recent methods of producing, reproducing, changing, controlling, reinforcing, and measuring sound. The 1,248-page Handbook sells for $79.95. Contact Howard W. Sams & Co, 4300 W 62nd St, Indianapolis, IN 46268, tel 317-298-5400.

The University of Surrey—A Self-Sufficient Research Center

Spacecraft engineering facilities at Surrey are broken down into three main areas of research:

- *Spacecraft engineering research*—research into spacecraft architectures, systems, technologies, components, and orbital operations.
- *Space education*—stimulation and support of space education at all levels (from schools and colleges through universities, including the Amateur Radio community). Surrey also offers a Master's Degree course in satellite communications engineering.
- *Surrey Satellite Technology, Ltd*—the transfer into industry of technology developed in the UoSAT unit is achieved through Surrey Satellite Technology Limited (SST), located on the University campus. SST was formed in 1985 by the University in a partnership with General Technology Systems. Its purpose is to provide a professional interface between the University and industry, to enable efficient technology transfer and commercial development of the ongoing research, and to undertake industrial contracts.

UoSAT 1 was launched Oct 6, 1981, and UoSAT 2 was placed in orbit Mar 1, 1984. Mission objectives for both space vehicles varied, but particular emphasis was on establishing the University as a world leader in the field of designing advanced, yet low-cost experimental satellites. Both UoSAT 1 and 2 are tracked with the latest technological developments from UoSAT's completely automated mission control center.

UoSAT-C is currently in the planning stages; mission outlines have already been prepared. This spacecraft will represent the third generation of UoSAT satellites, and its mission objectives are similar to its predecessors, encompassing space technology, engineering, communications, and education. Some of the experiments under consideration for UoSAT-C are:

- Space radiation environment experimentation.
- Store-and-forward digital communications experimentation.
- Advanced modulation/demodulation schemes.
- HF radiowave propagation experimentation.
- Spacecraft optical fiber data handling experimentation.

—Thanks goes to Dr Martin N. Sweeting, G3YJO, for supplying the ARRL with a brochure about the University of Surrey's UoSAT Spacecraft Engineering Unit.